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Procedia Computer Science 00 (2024) 000–000

Procedia Computer Science

www.elsevier.com/locate/procedia

6th International Conference on Industry 4.0 and Smart Manufacturing

Edge, Fog and Cloud Computing framework for flexible production

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Abstract

Industry 4.0 (I4.0) offers tremendous potential benefits across various sectors. Manufacturing can derive the greatest value from it. However, the rate of adoption remains low due to barriers such as management commitment, lack of knowledge, and costs. Simple solutions that require minimal investment and carry low risk are the best way to introduce I4.0 into companies. The shared data flow generated by sensors and the Industrial Internet of Things (IIoT) can provide valuable insights thanks to new connectivity between systems. This deeper knowledge enables the creation of highly flexible production systems capable of meeting customer demands and achieving mass customization. However, a key point too little addressed yet is that the intensity of data flow can lead to latency and data loss issues, resulting in a system unable to meet the real requirements as answers are provided too late. To address this challenge, the authors propose a framework based on the integration of Edge, Fog, and Cloud Computing, aimed at extracting maximum value from data by analysing it both locally and centrally. This approach reduces latency in production systems, enhances flexibility, and enables predictive maintenance. The result is an architectural framework that integrates Edge, Fog, and Cloud Computing to improve the flexibility of a multi-product manufacturing system. The implementation of I4.0 in existing Industry 3.0 plants facilitates flexible production capable of meeting mass customization requirements and achieving high resilience. In conclusion, it has been demonstrated that Edge, Fog, and Cloud Computing can be effectively integrated into a Flexible Production framework.

Peer-review under responsibility of the scientific committee of the 6th International Conference on Industry 4.0 and Smart Manufacturing

Keywords: Edge Computing; Fog Computing; Cloud Computing; Connectivity; Flexible production system; Industry 4.0

1. Introduction

Industry 4.0 is the current innovation wave, and it can bring huge value to any field. Among all of them, manufacturing can get the highest benefit. Connectivity is one of the main characteristics of the 4th Industrial Revolution [1]. This new possibility of data sharing can bring huge value in the manufacturing lines as information

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Peer-review under responsibility of the scientific committee of the 6th International Conference on Industry 4.0 and Smart Manufacturing

can be collected anywhere and be visible from anywhere. Moreover, the system is monitored in real time and it is possible to know the exact state of machines and components and maintenance teams can intervene as soon as required with precision. With an improved Statistical Process Control (SPC) [2], [3], [4], it is even possible to act before the failure occurs, with a predictive maintenance [5], avoiding disruption and damage spread [6]. The impacts of this kind of adoption are reductions in costs and downtimes. In fact, with precise interventions, it is possible to restore the system in less time. Another key benefit of I4.0 is the possibility for the system to self-adapt and adjust to the real conditions. As the variability of the requested output increases, the system must be able to face all the required changes. Customers are getting more and more demanding, and the mass customization becomes a necessity for many companies [7]. To achieve that, production must be flexible. Flexibility is indeed one of the main characteristics of I4.0 [8] and can make companies able to face the current fluctuations in markets. New technologies can in fact enable the system to switch from one batch to another, even if they are very different from each other. Advanced robotics are provided with devices to change tools quickly and automatically based on the desired outcome. The ability to switch from a production to another is very important to meet the needs of the market, but also to face problems that could occurs, like delays, missing spare parts [9]. As Manufacturing systems are very complex, with thousands of variables correlated to each other, it becomes fundamental to adopt systems able to collect data in real time and perform calculations, which can be sometimes time consuming [7]. This issue increases in severity when the data flow gets bigger and bigger, up to becoming Big Data [10]. In that case, the latency of system can become a very severe limitation to the exploitation of data, whose main value comes from the real time production [11]. In a time-evolving system, timing can be crucial to act with effectiveness. Then, depending on the speed of change, latency can affect the data sharing process at the point to strongly reduce the potential value of the real time monitoring. Another aspect to consider is the cost of the data management architecture and cybersecurity. The barriers of an on-premises system are very high for most businesses: first, the cost of building a on premises system is very high and for most of companies it is unsustainable [12]; secondly, all the maintenance costs and the required knowledge to create the architecture would be another great block to this way [13]. Services are then a way better solution than on premises ones, as they can be set based on real consumption, minimizing costs and risks, as, with a proper Service Level Agreement (SLA), the provider ensure a certain level of redundancy and data security. As data contains great value, but its management can be costly and cause latency, a centralized solution could not be the ideal one [14]. For this reason, just using Cloud could end in an unsustainable system, too busy and giving answers too late. To avoid this, local and peripheral computations are a viable solution to this future problem [7]. Using Edge and Fog computing, it is possible to analyse data where they are collected [15] and then, once the firsts evaluations have been carried out, the information is sent to Cloud. Here, the centralized system can elaborate the most in-depth analysis, using data already cleaned and structured [16]. Following the above-described idea, the Authors present their innovative architectural framework based on Edge, Fog and Cloud Computing, to improve the flexibility of industrial plants. Edge computing is crucial because it allows data to be processed locally, near the source, enabling immediate response to operational conditions. Fog computing serves as an intermediary layer between the Edge and Cloud, providing additional processing capacity closer to the production site. This decentralization enables more complex analyses to be performed locally without overwhelming the central Cloud infrastructure. Fog nodes can handle data aggregation and pre-processing, reducing the volume of data that needs to be sent to the Cloud and thereby minimizing bandwidth usage. Cloud computing still plays a critical role in long-term data storage, advanced analytics and strategic decision-making. The Cloud provides the computational power and scalability needed to analyse large datasets aggregated from multiple Edge and Fog nodes, facilitating long-term improvements in production strategies, forecasting and operational efficiency. By integrating these three layers, the Authors aim to create a highly responsive, adaptable and resilient production system that can meet the challenges of modern manufacturing. This architecture provides the flexibility required to switch between product variants, handle sudden changes in demand and optimize machine uptime, ultimately enhancing the competitiveness of the manufacturing operation in an Industry 4.0 context.

The paper is divided into sections as follows: Problem Statement and Research Questions (RQs); the followed methodology; the existing literature review on the topic with pros, cons and gaps; the Authors' framework; the results and the discussions; the conclusions and the future work agenda. The paper is structured as follows: The Theoretical Foundations section provides an overview of IIOT technologies, Edge Computing, Fog Computing, and Cloud Computing, outlining their characteristics and benefits. The Methodology section describes the selection criteria, and the working method used for integrating these technologies into IIOT systems. Subsequently, the Literature Review examines existing studies and identifies research gaps. The Conceptualization section details the description of the manufacturing system considered, the integration of technologies, and case studies or simulations. Finally, the Results section presents data analysis and technology comparisons, followed by a Discussion on practical implications, study limitations, and future prospects. The Conclusions summarize the key findings and offer practical recommendations for the manufacturing sector.

2. Problem statement and research questions

Industry 4.0 can bring huge benefits in manufacturing, making it flexible. However, most of companies lack in implementing the 4.0 technologies due to lack of knowledge, costs and other barriers. To reduce the potential resistance to adoption, the Authors' philosophy is "starting small". The current solutions are not fully implemented and risk to meet internal resistance. Moreover, a future problem of most of 4.0 systems, when they collect data from complex facilities, is the data flow management. This problem will become more and more severe with Big Data. As clear solutions are still very scarce, there is a need to develop more architectures which can face the above-mentioned problems, while, at the same time, bringing the value of I4.0 in the domain of flexible production. The previous problem statement has been translated into the following Research Questions:

1. What are the characteristics of Edge, Fog and Cloud Computing that can be applied to Flexible Production?
2. How can Edge, Fog and Cloud Computing be integrated into a Flexible Production 4.0 framework?
3. Which will be the effects of this kind of framework in bringing I4.0 into 3.0 companies?

First, the single technologies are evaluated and correlated to Flexible Production. Once this has been done, the next RQ concerns the integration of them into a full system, to overcome the problems stated before. Finally, the designed architecture is studied in its potential to reduce the potential resistance to I4.0 adoption.

3. Materials and methods

A deep insight into the existing literature has been carried out by using the database Scopus, aiming to the maximum quality of the novelty of this paper. The chosen strings of keywords are: ("Edge computing" OR "fog computing" OR "Cloud computing") AND ("production" OR "manufacturing") AND ("flexib*"). The 1st string focuses on the 3 technologies of interest for this paper. The 2nd and 3rd evaluate the impact on production flexibility. A total amount of 684 papers has been found, reduced with filters in cascade. The first and the second string have been searched only among the keywords of the articles (236 papers). Secondly, to evaluate the most recent trends and applications of highest quality, only the last 10 years (212) on journals (95) in English have been considered (92). Finally, the subject areas of interest have been limited to "Computer science", "Engineering", "Business, management and accounting", and "Decision science", obtaining 83 papers, of which 71 are available to read. These 71 papers were carefully analysed, removing those out of scope. The final sample was thus formed by 48 records. To this amount, other 20 papers known by authors have been added to further increase the quality of the paper and state its novelty. Prisma Model is reported in Fig. 1 in appendix A.

About the case study, 6 months data have been used to make the analysis about latency and flexibility. Moreover, a statistical test has been carried out to prove the reliability of the results.

4. Literature review

Increasing customization is driving manufacturers to develop more flexible manufacturing systems [17], [18], [19]. Furthermore, with the rapid development of information and communication technologies, industrial manufacturing environments and requirements are changing considerably [20]. To address this, Cloud Computing is reshaping the manufacturing industry into a dynamically scalable, on-demand, service oriented, and highly distributed cost-efficient business model [21], [22], [23]. Cloud Computing offers scalable data centres, either on-premises or in the Cloud, to store and process Big Data [24], [25] from IIoT devices [11]. It is a powerful and flexible platform [26], [27] that provides sufficient resources and services for data management and enables direct connectivity for IIoT devices to the

Cloud [10], [8], [28], virtualizing a network of servers as a vast resource pool to offer flexible storage and computing capabilities [29], [30], [31]. By using a Cloud Computing architecture and high-speed networking, the Cyber Physical System can be operated and controlled without any human physical intervention by on-demand access to a shared pool of computing resources that can be rapidly provisioned and released [32], [33] from different geographical locations [34], [35], [36], thereby improving real-time performance and accuracy [9]. Despite the capabilities of Cloud Computing in computing, storage, and connectivity, it struggles with the increasing volume of data. To tackle this challenge, some data processing should be decentralized to the edge [10], [37]. This shift has led to the integration of Edge Computing into Cloud Computing as a growing trend [38]. Edge Computing functions as an open platform encompassing network, computing, storage, application, and other functionalities [39]. It processes, analyses, and stores information near the data source at the edge of the network and closer to the devices [7], thereby reducing traffic and communication bandwidth [40], [14], [41], [1]. Unlike the Cloud, which directly stores insignificant data and noise, Edge Computing allows for local filtering, caching, [42], [15] and running intelligent software packages [43] to support manufacturing services and activities [44]. Moreover, Edge Computing enables practical AI solutions in industrial environments with limited network bandwidth [45], [46]. Consequently, Edge Computing has emerged as an advanced technique providing scalable resources for IIoT devices to analyse industrial data and enhance productivity [47]. However, Edge devices often lack sufficient resources to run high-performance applications, such as intelligent reasoning models. Thit’s why Fog Computing may be employed to support data acquisition, enhance machinery integration with IIoT, and enable Cloud manufacturing [16], [48]. Fog Computing serves as an intermediate layer between the Edge and the Cloud, bridging the processing power gap between these two entities. Data that does not necessarily require transmission to the Cloud is processed within the Fog layer devices, thereby reducing response times [49]. This decentralization with local high processing capacity and low latency positions Fog Computing as a gateway and filter. It manages data frequency from sensors and handles unstructured data, leveraging the advantages of local processing, offloading sensors, and connectivity to cloud resources. This approach supports intelligent sensors across communication interfaces, mobility, data processing, security, and scalability [50]. Unfortunately, the distributed, collaborative, and dynamic characteristics of Fog Computing introduce numerous new security and privacy challenges [51]. The fusion of Cloud Fog and Edge Computing enables the offloading of computational tasks from Cloud Computing, effectively reducing latency [52]. This integration makes it possible in the smart manufacturing domain to achieve performance and operational efficiencies by facilitating rapid decision-making processes for automated devices operating on the factory floor [53], [54], [55]. In the analysed literature, no framework models were found, showing the need to research in this direction. For this reason, more papers have been analysed with a snowballing. The Fog, Edge, and Cloud Computing frameworks, while integrated with IoT, face significant challenges in scalability, latency, security, and integration [20]. Edge and Fog Computing improve system resilience by decentralizing data processing, but they require complex and expensive infrastructure for quick recovery from failures. Cyber-resilience is then essential, but securing Edge and Fog nodes remains difficult [40]. In terms of scalability, Fog Computing decentralizes workloads but struggles with network traffic management and scaling across large systems [51]. Cloud Computing, while effective at processing large amounts of data, suffers from latency issues and security risks, particularly when connected to vulnerable IoT devices [48].

5. Choice of the case study

The consumer electronics sector is characterized by rapid technological advancements, high demand variability and customized products. These dynamics make it an ideal case for studying the application of flexible production systems. The complexity and variability in production processes within consumer electronics align closely with the challenges that I4.0 is designed to address, such as real-time data processing, adaptability to frequent product changes and the need for high operational efficiency. Moreover, the findings of this study can be generalized to other sectors that face similar operational challenges: High Variability, Customization Needs, Use of Advanced Technologies, Operational Scale, Data Availability. Following these characteristics, a manufacturing facility operating in the consumer electronics sector has been selected. The facility produces a wide range of electronic devices, from small appliances to customized technological gadgets, requiring significant flexibility in production operations. This facility provides an ideal context for studying the integration and impact of Edge Computing, Fog Computing, and Cloud Computing technologies on flexible production. Its complexity and operational variability offer a rich data environment and challenges, making it a significant case study for IIOT implementation. In this domain, the aspects that a flexible production must have are:

- Adaptability to Demand Variations: The facility is designed to quickly modify production lines and processes based on demand fluctuations, reducing downtime and improving efficiency.
- Product Customization: Production lines and equipment are configurable to produce small batches of customized products, meeting specific customer requirements.
- Operations Organization: Operations are modularly organized, with multidisciplinary teams that can be rapidly reassigned to different production lines or projects. The use of IIOT technologies enables agile real-time resource management and continuous performance monitoring.

6. Architecture / Framework

6.1. *The proposed architecture*

The proposed architecture for integrating Edge, Fog, and Cloud Computing in the IIOT system of the aforementioned manufacturing facility consists of various components to maximize the strengths of each technology, ensuring fast response times, efficient bandwidth usage, data security, and advanced analytics capabilities. As a result, the manufacturing facility can quickly adapt to demand fluctuations and enhance flexible production. The following detailed description outlines the composition and flow of data and materials:

1. **Edge Level**:
   a. Adaptability to Demand Variations: The facility is designed to quickly modify production lines and processes based on demand fluctuations, reducing downtime and improving efficiency;
   b. *Edge Devices*: These include intelligent sensors and local actuators responsible for collecting and immediately processing data. Examples include temperature, humidity, vibration sensors, and actuators in automation systems;
   c. *Microcontrollers and PLCs*: They perform real-time control of production operations, ensuring a quick and autonomous response to variable process conditions.
2. **Fog Level**:
   a. *Fog Nodes*: Located near production, Fog nodes gather pre-processed data from Edge devices, perform more complex analyses, and orchestrate communication between Edge and Cloud levels. These nodes can include local servers and advanced gateways;
   b. *Fog Computing Services*: Provide functionalities such as predictive analytics, preventive maintenance [56], and process optimization. Fog nodes reduce latency and enhance operational resilience.
3. **Cloud Level**:
   a. *Cloud Platforms*: Offer massive storage capacity and computational power for processing large volumes of data. Examples of Cloud services used include AWS, Microsoft Azure, and Google Cloud;
   b. *Advanced Analytics Services*: Utilize artificial intelligence and machine learning techniques to extract insights from aggregated data and support long-term strategic decisions.

This architecture underlines a data and material flow, represented as follows:

1. **Data Collection**: Edge sensors collect real-time operational data and send raw data to Edge devices for initial processing. Pre-processed data is transmitted to Fog nodes via secure gateways for further analysis and integration.
2. **Data Processing**: In Fog nodes, data is analysed to identify patterns, anomalies, and optimization opportunities. Analysis results are used for immediate operational decisions. Processed data and analysis results are then sent to the Cloud for long-term storage and further strategic analysis.
3. **Feedback and Control**: Fog and Cloud analysis results are used to optimize production processes. For instance, Fog-based predictive maintenance can reduce machine downtime. Strategic decisions derived from

Cloud analytics are implemented at the Edge and Fog levels to continuously improve production efficiency and flexibility.

6.2. *Technical details of the proposed framework*

Fig. 2 in Appendix B depicts a system architecture for Edge-Fog-Cloud computing within two separate warehouses, each containing multiple production lines (Warehouse A has two, Warehouse B has three). The architecture highlights the flow of data from Edge devices in production lines to Fog nodes and to the Cloud for centralized processing.

6.3. *Key Components of the proposed framework:*

- **Edge Level** (Warehouse A and B): On each production line, there are sensors and actuators attached to Printed Circuit Boards, labelled as "Sensor + PCB" and "Actuator + PCB". These represent the Edge devices responsible for collecting data (Sensors) and controlling actions (Actuators) on the production line. The Sensors and Actuators on the production lines are marked as part of the Edge level in the hierarchy, because of the attached PCB configuration and capabilities (data sampling, filtering, storing and elaborating);
- **Fog Level**: In Warehouse A, the data from the Edge devices is sent to a Zone Gateway, which acts as a Fog node. It processes and integrates the data (from each PCB, Production Line level; Line 1 with Line 2, Warehouse A level) before sending it further to the Cloud. In Warehouse B, the Fog level is represented by a Local Server, which is more structured and robust than the Zone Gateway used in Warehouse A; it processes the data from multiple Production Lines in a similar way as the Zone Gateway in Warehouse A. The connection between the Edge and Fog layers in both warehouses is facilitated using the MQTT protocol (Message Queuing Telemetry Transport), a lightweight messaging protocol suitable for constrained environments.
- **Cloud Level**: The Fog nodes (Zone Gateway in Warehouse A and Local Server in Warehouse B) transmit the processed data to a Server, which constitutes the Cloud. The Cloud server receives and aggregates the data from both Warehouses for processing, analysis or storage.

6.4. *Flow Description*

- **Edge to Fog**: PCBs governing Sensors and Actuators collect real-time data on production lines, which is transmitted to the local Fog nodes (Zone Gateway or Local Server) using MQTT protocol. The Edge nodes process and analyse the data at a local level to reduce latency and bandwidth usage.
- **Fog to Cloud**: The Fog nodes process and analyse the data at a local level to further reduce latency and bandwidth usage. The processed data is then sent from the Fog nodes to the Cloud server for centralized storage, advanced analytics or further decision-making processes.

6.5. *MQTT (Message Queuing Telemetry Transport)*

In Edge-Fog-Cloud computing frameworks, several protocols are recommended for their specific roles in communication, data management and system integration. After a careful review of the options available the Authors opted for the MQTT mainly for the following reasons: Lightweight and Low Power, MQTT is a lightweight publish-subscribe messaging protocol ideal for low-power devices, which are often found at the Edge level; Low Bandwidth Usage, MQTT is designed for constrained environments with limited network bandwidth, making it suitable for IOT devices in Edge and Fog environments; Asynchronous Communication, MQTT supports asynchronous communication, which is useful in distributed environments where Edge devices might not always be continuously connected to the network; Use Case, MQTT is suitable for Edge devices that send small packets of data, such as Sensors and Actuators in an industrial IIoT environment.

7. Case Study

In this section are reported the impact of the framework over latency and production flexibility. These characteristics are the basis for flexibility in production. In Table 1, Table 2, Table 3, Table 4 and Table 5 and Table 6 respectively in Appendix C, Appendix D, Appendix E, Appendix F, Appendix G and Appendix H, the results are reported.

About **latency reduction**, Edge devices have been used in an automatic assembly line, equipped with vibration and temperature sensors, to monitor machine operational conditions in real-time. Sensors continuously collect data and send it to Edge devices for immediate processing. Any anomalies, such as excessive vibrations, are detected and instantly reported to operators and control systems, triggering corrective measures without delays. Average latency decreased from 150 ms (measured in previous configurations without Edge Computing) to 20 ms (achieved after implementing Edge devices). This reduction was quantified using real-time monitoring tools and digital timers. Moreover, the frequency of failures decreased by 30%, as evidenced by the number of machine downtime incidents recorded in maintenance logs during a six-month observation period before and after the implementation of Edge Computing. This decrease is attributed to the ability to quickly detect and correct operational anomalies.

About **production flexibility**, as the market demands high product customization, with frequent changes in customer specifications, is strongly required. Using 3D printers and flexible assembly lines controlled by PLCs connected to Edge devices and Fog nodes, the plant can quickly adapt to new demands. Customer specification data is processed in the Cloud and transmitted to Edge devices to configure production lines in real-time. The results are: Better Response Time (ms), improvement of 86,7%, measures how quickly the system can respond to operational changes or anomalies. A shorter response time indicates higher operational efficiency; Fault frequency, improvement of 30%, how many faults happen in a month in average; Machine Downtime (hours), improvement of 25%, total time during which machines are non-operational due to maintenance or faults. Reductions in downtime indicate greater machine availability; Energy Efficiency (%), improvement of 17,6%, ratio of energy effectively used for production to total energy consumed. A higher value indicates better energy resource management; Setup Time (hours), improvement of 40%, time required to switch from one production setup to another. A reduction in setup time highlights increased production flexibility; Number of Product Variants, improvement of 50%, the plant's capacity to produce different product variants without significant production interruptions. A higher number of variants indicates greater customization capability and adaptability.

8. Result and discussion

The **1st result** is from literature. It emerges that the transformation of manufacturing through Cloud, Fog, and Edge Computing enables manufacturers to achieve greater flexibility, efficiency, and responsiveness in meeting the demand of modern industrial environments.

The **2nd result** is the framework proposed. It has been shown that Edge, Fog and Cloud Computing can be perfectly integrated, providing great value. The possibility to integrate those technologies open new horizons of Industry 4.0 implementations in different kind of companies, which have their own requirements.

The **3rd result** consists of the possibility to evaluate the framework focusing on latency reduction and enhancements in production flexibility.

The **4th result** comes from the case study, which showed that the implementation of Edge devices significantly reduced the time required for data processing and response, as shown in Table 1 in Appendix C. The reduction in latency (up to 86.7%) demonstrates a significant improvement in the facility’s ability to respond to real-time operational conditions. This decrease in latency contributes directly to more efficient production processes and a reduction in machine downtime.

The **5th result** is directly correlated to flexibility, the ability to quickly adapt to varying production demands. With the integration of Edge and Fog computing technologies, the facility was able to significantly enhance its flexibility in responding to changes in customer demands and product customization requirements. The setup time required to switch between production configurations was reduced by 40%, enabling the facility to respond more quickly to changes in customer specifications. Additionally, the number of product variants that could be produced within a given month increased by 50%, reflecting the system's enhanced adaptability. Fault frequency, a key measure of production interruptions, also decreased by 30%, highlighting the role of real-time monitoring and data analytics.

To further substantiate the improvements reported, a statistical analysis of the key performance metrics was conducted. A paired sample t-test was applied to compare the system's performance before and after the implementation of Edge, Fog and Cloud computing technologies. The results of the t-test are summarized in Table 4 in Appendix F. The t-test results indicate statistically significant improvements in latency reduction ($p < 0.001$), machine downtime ($p = 0.002$), maintenance failures ($p = 0.004$) and setup time ($p < 0.001$), confirming that the improvements observed were not due to random variation. These results provide strong evidence supporting the claim that the integration of Edge, Fog and Cloud computing technologies significantly enhanced production efficiency, maintenance reliability and operational flexibility. The results demonstrate that the Edge-Fog-Cloud framework proposed by the Authors delivers tangible benefits in terms of latency reduction, predictive maintenance and production flexibility. The data clearly show improvements across all key performance areas, with significant statistical backing. The reduction in latency has enabled real-time responsiveness in the manufacturing system, ensuring minimal delays in detecting and correcting operational anomalies. Predictive maintenance has optimized machine uptime, reduced maintenance-related failures and improved energy efficiency, contributing to overall production stability. The increased production flexibility, as evidenced by the reduction in setup time and the greater number of product variants produced, highlights the system's ability to meet varying customer demands in an efficient and timely manner. These improvements make the manufacturing facility more resilient and adaptable, key factors for maintaining competitiveness in a dynamic industrial landscape. The findings from this study not only confirm the value of integrating Edge, Fog and Cloud computing in a high-variability sector like consumer electronics, but also suggest that similar results can be achieved in other industries with comparable production challenges. Future research could further explore the scalability of this framework and investigate its applicability in other sectors, such as automotive or healthcare, where real-time data processing and system flexibility are equally critical.

9. Conclusion

Industry 4.0, with data share and connectivity, can provide great value in companies. The knowledge about the system can be strongly improved and this will bring new opportunities for enhancing competitiveness in a fast-changing world. The data flow, however, requires strong systems to be collected and correctly analyzed. A centralized system cannot in fact manage Big Data. To solve this problem, decentralization is the key. With Edge, Fog and Cloud Computing it is possible to analyze data close to the source and aggregate the results of the first evaluations. With a reduction of response times (-86.7%), fault frequency (-30%), downtimes (-25%), energy consumption (17.6%), setups (-40%) and improved product variability (+50%), the system becomes a lot more flexible. Then, it is possible to conclude that Industry 4.0, and in particular Edge, Fog and Cloud Computing are pivotal for reaching a true flexible production. Future works will extend this framework to Artificial Intelligence [57] and its cognitive capabilities [58] and Digital twin [59], taking into consideration different sectors, like healthcare [60], [61] and energy [62], applied in different activities, from warehouse [63], [64] to supply chain, and focusing also on resilience, sustainability [65], [66] and safety [67]. To successfully reach these goals, it is mandatory for researchers to ensure cybersecurity in an effective way, taking advantage of the ability of this system to isolate infected blocks. Moreover, studies associated to the company size to the need of edge and fog computing should be addressed, providing clearer definition of these 2 technologies. Different kinds of analysis and simulations should be studied to face system stochasticity [68], [69].

Appendix A. PRISMA Model

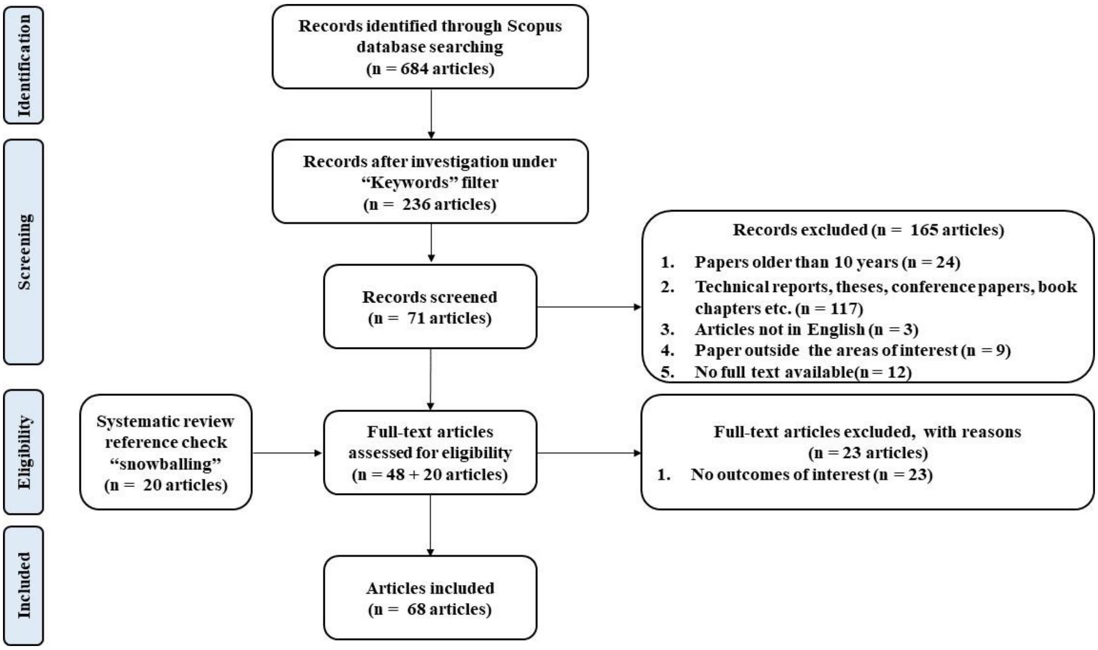


Fig. 1 - PRISMA Model

Appendix B. System architecture for Edge-Fog-Cloud computing

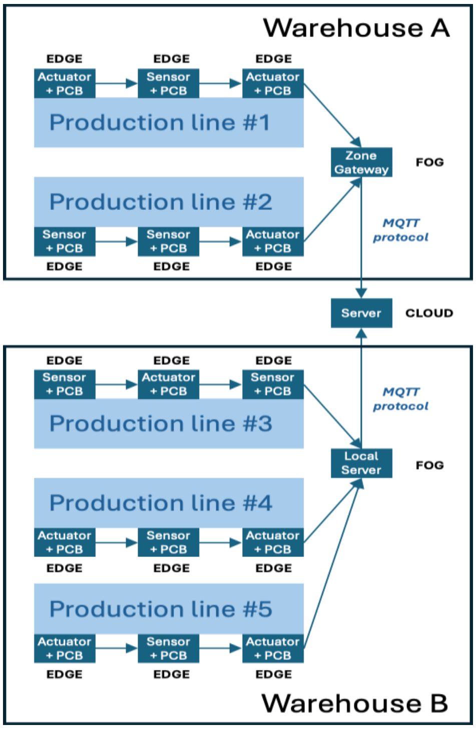
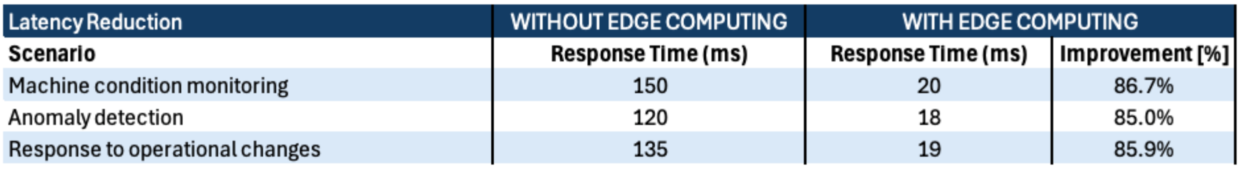


Fig. 2 - System architecture for Edge-Fog-Cloud computing

Appendix C. Latency Comparison Before and After Edge Computing Implementation

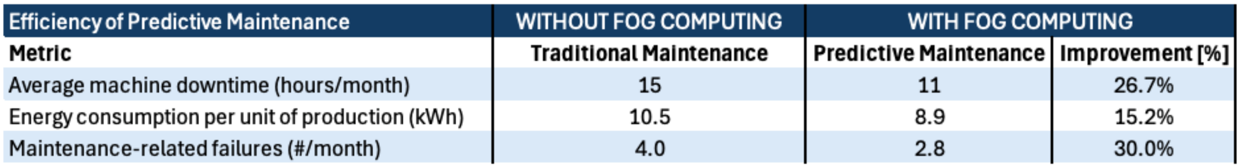
Table 1 - Latency Comparison Before and After Edge Computing Implementation



Latency Reduction	WITHOUT EDGE COMPUTING	WITH EDGE COMPUTING	
Scenario	**Response Time (ms)**	**Response Time (ms)**	**Improvement [%]**
Machine condition monitoring	150	20	86.7%
Anomaly detection	120	18	85.0%
Response to operational changes	135	19	85.9%

Appendix D. Maintenance Metrics Before and After Fog Computing Implementation

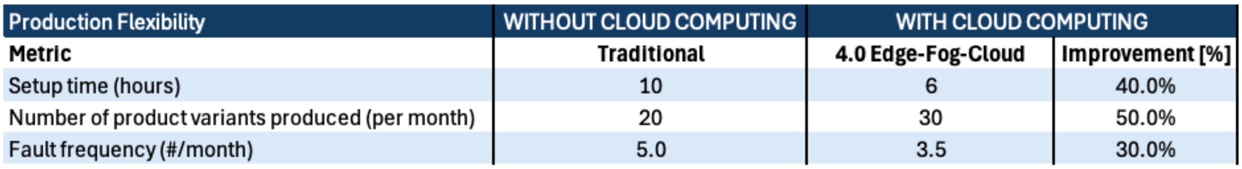
Table 2 - Maintenance Metrics Before and After Fog Computing Implementation



Efficiency of Predictive Maintenance	WITHOUT FOG COMPUTING	WITH FOG COMPUTING	
Metric	**Traditional Maintenance**	**Predictive Maintenance**	**Improvement [%]**
Average machine downtime (hours/month)	15	11	26.7%
Energy consumption per unit of production (kWh)	10.5	8.9	15.2%
Maintenance-related failures (#/month)	4.0	2.8	30.0%

Appendix E. Production Flexibility Metrics

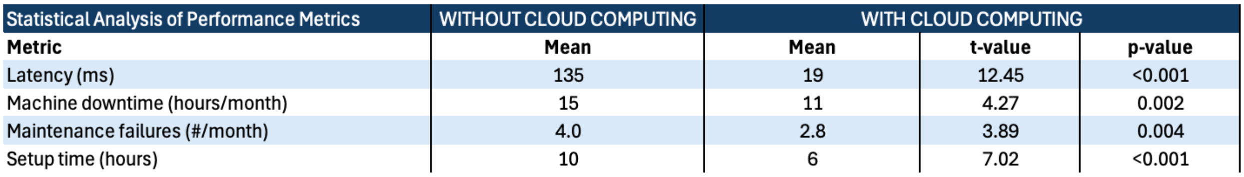
Table 3 - Production Flexibility Metrics



Production Flexibility	WITHOUT CLOUD COMPUTING	WITH CLOUD COMPUTING	
Metric	**Traditional**	**4.0 Edge-Fog-Cloud**	**Improvement [%]**
Setup time (hours)	10	6	40.0%
Number of product variants produced (per month)	20	30	50.0%
Fault frequency (#/month)	5.0	3.5	30.0%

Appendix F. Statistical Analysis of Performance Metrics

Table 4 - Statistical Analysis of Performance Metrics



Statistical Analysis of Performance Metrics	WITHOUT CLOUD COMPUTING	WITH CLOUD COMPUTING		
Metric	**Mean**	**Mean**	**t-value**	**p-value**
Latency (ms)	135	19	12.45	<0.001
Machine downtime (hours/month)	15	11	4.27	0.002
Maintenance failures (#/month)	4.0	2.8	3.89	0.004
Setup time (hours)	10	6	7.02	<0.001

Appendix G. Latency, efficiency and flexibility improvement

Table 5 - Latency, efficiency and flexibility improvement

Data for the first half of 2023

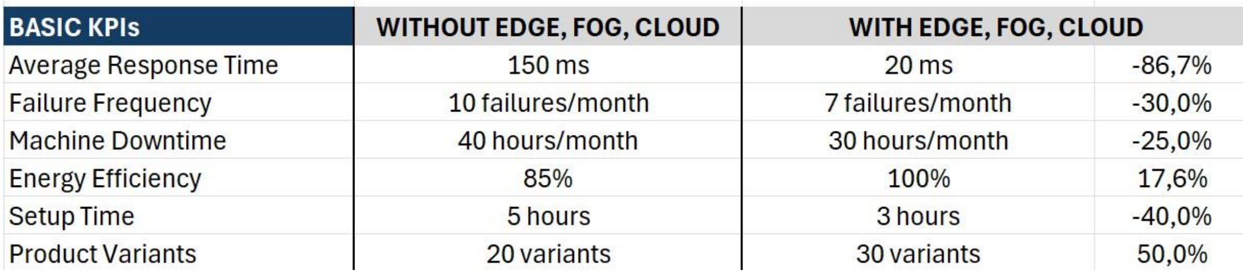
Latency Reduction	WITHOUT EDGE COMPUTING		WITH EDGE COMPUTING			
Month	**Response Time (ms)**	**Failures (number)**	**Response Time (ms)**	**[%]**	**Failures (number)**	**[%]**
January	160	12	25	-84,4%	9	-25,0%
February	155	11	23	-85,2%	8	-27,3%
March	150	10	22	-85,3%	8	-20,0%
April	150	10	21	-86,0%	7	-30,0%
May	145	9	20	-86,2%	7	-22,2%
June	140	8	20	-85,7%	7	-12,5%

Efficiency of Predictive Maintenance	TRADITIONAL MAINTENANCE (WITHOUT FOG COMPUTING)		PREDICTIVE MAINTENANCE (WITH FOG COMPUTING)			
Month	**Machine downtime (hours)**	**Energy Efficiency (%)**	**Machine downtime (hours)**	**[%]**	**Energy Efficiency (%)**	**[%]**
January	45	80	35	-22,2%	95	18,8%
February	42	82	34	-19,0%	97	18,3%
March	40	85	32	-20,0%	98	15,3%
April	39	85	31	-20,5%	99	16,5%
May	38	86	30	-21,1%	100	16,3%
June	37	87	29	-21,6%	100	14,9%

Production Flexibility	WITHOUT CLOUD COMPUTING		WITH CLOUD COMPUTING			
Month	**Setup Time (hours)**	**Product Variants**	**Setup Time (hours)**	**[%]**	**Product Variants**	**[%]**
January	6	18	4	-33,3%	25	38,9%
February	6	19	4	-33,3%	26	36,8%
March	5	20	3	-40,0%	28	40,0%
April	5	20	3	-40,0%	29	45,0%
May	4	21	3	-25,0%	30	42,9%
June	4	21	3	-25,0%	30	42,9%

Appendix H. Basic KPIs improvement

Table 6 - Basic KPIs improvement



BASIC KPIs	WITHOUT EDGE, FOG, CLOUD	WITH EDGE, FOG, CLOUD	
Average Response Time	150 ms	20 ms	-86,7%
Failure Frequency	10 failures/month	7 failures/month	-30,0%
Machine Downtime	40 hours/month	30 hours/month	-25,0%
Energy Efficiency	85%	100%	17,6%
Setup Time	5 hours	3 hours	-40,0%
Product Variants	20 variants	30 variants	50,0%

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