Resilience 4.0 in beer production line:

IoT, Edge Computing, Fog Computing, and Cloud

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Abstract: The **purpose** of this research is to analyze the impact of Industry 4.0 (I4.0) on the Resilience of a beverage production line, particularly a beer one. As this characteristic is fundamental in any field, it must be addressed also in the field of Industry 4.0. The new technologies made available by the Fourth Industrial Revolution can bring huge benefits on the production plants on different aspects, like: predictive and prescriptive maintenance, increased OEE, productivity, efficiency, and effectiveness; better quality of output and customer satisfaction. In this paper, the chosen 4.0 technologies are IoT, Edge Computing, Fog Computing, and Cloud. This choice has been made to follow on of the pillars of Industry 4.0: starting small. This research focuses on field level, with IoT, and the management of the collected data by the integration of Edge Computing and Fog Computing, before sending the final data to Cloud. The **methodology** used to write this paper is divided into clear steps, logically connected to each other. The first activity has been a deep analysis and study of the existing literature, to understand the features of each technology and their strengths and weaknesses. Moreover, it has also been searched for how to integrate these technologies and their impact on the Resilience of systems embedded with them. After this deep literature review, the next phase was to evaluate the requirements and needs of the beer production line, to establish how the studied technologies can bring value. Finally, the focus on Resilience has been set. The **key findings** of this research are the characteristics of the analyzed technologies and the impact on Resilience. The value of this innovative paper is the deep study of the field technologies and the design of a framework to bring Resilience 4.0 into production companies, especially to beer production lines.

Keywords: IoT, Edge Computing, Fog Computing, Cloud, Resilience 4.0

1. Introduction

(I4.0) presents a lot of technologies, and its main characteristic is data connectivity (Malatji et al., 2022). The growth in volume and velocity of generation of data make them become Big Data, which requires to be carefully managed or the system will not be able to sustain it and most of the information will be lost (Sandoval et al., 2019). The costs for the infrastructure risk to be overwhelming even for large corporations (Chang et al., 2016). It is important to evaluate what technologies are available and their integration. Data management infrastructure is a key point for each sector and entity, both big and small. Another aspect is Resilience, the ability to recover from disaster (Ahmad et al., 2024). Higher it is, less a system is fragile and can face adverse events. 4.0 technologies can help to enhance it. With online real-time data share, it is possible to increase knowledge over the entire system and deepen it into the single components. This study aims to provide a better understanding of Edge computing, Fog computing and Cloud computing. Then, it has been studied how to integrate those technologies with Industrial Internet of Things (IIoT), creating a framework that starts from sensor data collection to data analytics on the Cloud. Key characteristic is the possibility to manage high volume of data of different type. Once the framework has been explained, it has been addressed how it can enhance the Resilience of the system in which it is applied. Finally, this innovative framework for Resilience 4.0 has been adapted to be implemented into a beer production line, with the aim of increasing its performances and get the potential that I4.0 can offer. The paper is divided into the following sections: **Background** on Edge/Fog/Cloud computing and IoT; **problem statement** and its conversion into **research questions**; the **methodology** used to get the results; the **existing literature**, how to integrate the technologies, their impact over resilience and the applications on beer production; the single **technologies applications applied by authors** to resilience; **author's framework**; **results**; **discussions**; **conclusions**.

2. Background

2.1 Edge Computing

Edge Computing is based on computing devices at the edge of the network (Kim et al., 2020), whose aim is to process delay-sensitive services to achieve a real-time demand response when low latency is strictly required. A technology which can help a lot this last point is 5G (Ahmad et al., 2024; Ding and Janssen, 2018). 5G, integrated with a multi-access edge computing (MEC) can provide near instantaneous communication inside industry (Thiruvasagam et al., 2021). Edge can be integrated into an architecture with a highly-capable serve or it can be local, where local nodes provide collaboratively computational capacity (Ahmad et al., 2024). The advantages of this technology are resources efficiency, reliability and privacy, as data a processed locally (Ahmad et al., 2024), less dependency from Cloud, better context awareness and manageability of local systems (Kim et al., 2020). A first aspect to evaluate is data quality. In fact, data provided by Edge nodes must be validated, like with digital identity of the generating device and other devices cross-checking (Balistri et al., 2022). A main concern is computational power, its limited hardware could lead to cyber-attacks. Then, every data must be encrypted (Ahmad et al., 2024).

2.2 Fog Computing

Fog Computing is based on data analysis carried out by servers closer to user than Cloud. It is made by smart gateway which send data and the first analysis, like a warning if a parameter exceeds the control bars, to Cloud (Yu et al., 2018). These nodes manage metadata, software, computing, caching and networking applications (Ahmad et al., 2024). Fog computing is a layer between Edge computing and Cloud computing with computational and storage services, in the optic of resource continuum, from remote high-performance infrastructure to near-to-data embedded devices (Zanella et al., 2022). Its characteristics are location awareness, geo-distribution, low latency and mobility support (Yu et al., 2018). Fog Computing can be used in different fields, like autonomous vehicles, wireless sensors and actuators networks, smart cities, Health (Yu et al., 2018). Health Fog is an application which aims is to keep monitored patients' health information (Yu et al., 2018). The main concern is security from cyber-attacks and to understand how fine-grained the access control should be set with cryptography. Fog devices are closer to users, and then side channel attacks (Physical ones) can be performed (Yu et al., 2018). Moreover, Fog has a lower computational power than Cloud, due to its simpler hardware, and thus every shared data must be encrypted (Ahmad et al., 2024). Fog nodes, to communicate, mainly lean on cellular technology, like 5G, and limited coverage areas could lead to congestion and slowdowns (Ahmad et al., 2024). A run-time management system to increase nodes efficiency and a mapping application to send data to idle devices can help (Zanella et al., 2022). A challenge of Fog is the management of the entire system to fully exploit the devices, which require a unified programming model for modular applications and a system for transparent distribution of tasks (Zanella et al., 2022).

2.3 Cloud Computing

Cloud computing is widely adopted (Sharma et al., 2022) and enables companies to have access to enough processing power to manage large data sets (Fisher et al., 2020) and develop complex simulations, like multi-agents ones (Sethia and Karlapalem, 2011) and Digital Twins (Fogli et al., 2024). Cloud can be used to improve Resilience by providing business alignments, agility, efficiency and integration for business competitive edge (Chang et al., 2016). It is important to create resilient software to be able to face cyber-attacks. The required characteristics are: identifying users; privacy; integrity; durability; confidentiality, security of Cloud and Big Data flow; physical protection (Chang et al., 2016). The cyber-security is the main concern about Cloud, as in (Malatji et al., 2022) even 29 best practices about this theme have been found out. Trust is indeed a critical factor in Cloud adoption (Gajek et al., 2021).

2.4 Internet of Things (IoT)

Internet of Things (IoT) enables physical objects to share data and receive input through the Internet by remote (Yu et al., 2018) with a pervasive and ubiquitous computing (Ahmad et al., 2024). Recently, its cost decreased and this enabled the massive production of data (Fisher et al., 2020), reaching, according to IDC, 60 billion of entities and a generation of 80 ZB of raw data, for a value of 1256.1 billion USD by 2025 (Zanella et al., 2022). In manufacturing it keeps monitored efficiency, maintenance requirements (Partovian et al., 2023), machine utilization, and safety (Corradi et al., 2022) (Mosca et al., 2023; Peron et al., 2022; Porta et al., 2020). IoT also enables a better risk assessment. In Supply Chain it provides better efficiency integrating real-time data from different facilities (Yadav et al., 2023) and warehouses (Mosca et al., 2022). It can be used in Tourism and transport for railways efficiency and effectiveness, better control systems, predictive maintenance, smart infrastructure, energy efficiency, and electric vehicles (Bracco and Fresia, 2023; Fresia and Bracco, 2023). In flights had reduced fuel cost more than 5% for Honeywell and helped Wind River to reduce overall operational costs with predictive maintenance and data driven flight management. Further applications are in hotels and kitchens (Verma et al., 2021), where it can be integrated with electronic noses, sensors for gasses and aromas. They can help to understand alcohol quantity, with a precision up to 92% (Mendoza Montoya et al., 2021). Security is a main concern (Ahmad et al., 2024) and trust a dominant requirement (Gajek et al., 2021). A future problem about IoT is the data flow management, as the over 50 billion devices will represent a huge traffic of data, especially when based on 5G (Sandoval et al., 2019), that could saturate the current network infrastructure. This will lead to bigger and bigger data centres, whose power consumption will be unsustainable (Zanella et al., 2022).

3. Problem statement and Research Questions

Industry 4.0 is the main current technology innovation. However, complete frameworks which integrate the different technologies are still missing. Furthermore, there is still confusion on the differences among Edge, Fog and Cloud computing. Clearing the air on that and integrate those technologies is fundamental. Finally, it is important to investigate how to implement them in industry, like in beer production lines. The problem was translated into the following research questions: 1) How can Edge, Fog and Cloud computing can be integrated with IIoT into a framework for Resilience 4.0? 2) What are the benefits this framework can have in a beer production facility?

3. Methodology

Literature discusses a lot about IoT, Edge, Fog and Cloud. However, the differences among these techs and their integration need further analysis. The first step was a deep analysis of existing literature using Scopus database. The knowledge found is fragmented and few papers have been written on the beer production linked to Industry 4.0, therefore 2 different searches have been carried out. The first has its focus on the technological aspect, roadmaps, and impact on the resilience. The research strings are ("fog computing" OR "edge computing" OR "cloud computing" OR "IoT" OR "internet of things") AND ("industry" OR "production line" OR "framework" OR "integration" OR "adoption" OR "roadmap") AND ("resilien*"). 1.921 have been found, then the following eligibility criteria have been used: searching within the only keywords (94)), this choice was taken to strictly reduce the number of records to only those that extensively dealt with the technologies, avoiding then those who just cited them; subject areas "Computer Science", "Engineering", "Decision Sciences", "Business, Management and Accounting", and "Economics, Econometrics and Finance"; only journals (39) in English (38). Of these, only 36 of the full texts were available. Just those which proposed architectures based on Edge/Fog/Cloud and/or carefully explaining technologies limits and potentials have been used (24). The second search has its focus on the beer production with the strings ("fog computing" OR "edge computing" OR "cloud computing" OR "IoT" OR "internet of things") AND ("industry" OR "production line" OR "framework" OR "integration" OR "adoption" OR "roadmap") AND ("Beer" OR "ale"). As the applications to beer are very little and rare, no further filters have been used, aiming to find every possible paper, and all the 29 papers have been considered, of which 22 were available to be read. However, just 8 were concerning beer and 4.0 correlation and then have been cited. To this number, to provide better insights, a snowballing of other 12 papers have been performed. After the literature review, authors developed their innovative framework to integrate Edge, Fog, and Cloud computing with IIoT to create a Resilience 4.0, respecting what required and providing what was missing. In the end, Heineken Ichnusa beer production line has been studied and the framework has been adapted to it.

4. Literature review

4.1 Integrations

Edge Computing can be integrated with IIoT providing a better performance, data security and privacy, and reduce operational costs (Ahmad et al., 2024; Escamilla-Ambrosio et al., 2018). Fog Computing can be integrated with Cloud Computing and IoT (Yu et al., 2018), enabling IoT to save energy with the choice of the traffic to each node (Al-Shammari et al., 2020; Escamilla-Ambrosio et al., 2018), small computation task and upload data to Cloud, where real-time analytics is performed (Yu et al., 2018). In (Zanella et al., 2022), the authors could reduce execution times by 66% with integration. Both Edge and Fog can take great advantage of Ultra-reliable low latency communication (URLLC) when they are integrated with Cloud and IIoT (Ahmad et al., 2024; Escamilla-Ambrosio et al., 2018), enabling system reliability increase, data-centres growth reduction and energy consumption (Zanella et al., 2022), a very important topic nowadays (Fresia et al., 2024). Cloud can be integrated with IoT to increase the value of both the technologies, by providing fast data process and real-time share (Akhtar et al., 2022). However, the architecture must be designed to be able to face cyber-attacks (Sharma et al., 2022). The integration of IoT and the others technologies with machines is called IT/OT layers convergence. This convergence is fundamental for a successful Digital Transformation, in which the different views of software, like MES and ERP, are integrated and aligned (Corradi et al., 2022).

4.2 Resilience

Resilience is the ability to restore after disturbances after an adverse event and it is a key pillar in industry to face disruption in crisis times and keep high the flexibility (Ahmad et al., 2024). Resilience can be empowered by the Industry 4.0 adoption (Parri et al., 2021) and should be already considered during the design of the systems (Ahmad et al., 2024). Resilience is widely studied in the Supply chain, where it takes the name of SCRes (Tian et al., 2024) and it is on the objective in the business integration across supply chain (Gajek et al., 2021). Another field of great interest is the Disaster Governance, where IoT can strongly improve Resilience by acting on 6 spheres of Smart Disaster Governance: information, communication, timeliness, effectiveness and efficiency, reliability, and ubiquity (Shahat et al., 2020). As Industry 4.0 is based on digital technologies, the main concern about is cyber-security (Cvitić et al., 2022). Resilience is then widely sought to create reliable systems (Blakley et al., 2022; Ivanov and Yan, 2023). In this field, it takes the name of cyber-resilience, a non-optional component for the continuity of every business and to mitigate risk (Gajek et al., 2021). Edge gateways can be set and be ready to face cyberattack, while keeping the flexibility hight (Balistri et al., 2022). Fog computing enables to isolate effectively infected nodes, preserving the others. In this way, the overall resilience of the system is indeed increased (Ahmad et al., 2024). Edge and Fog nodes, by decentralizing analysis, increase the overall Resilience (Ahmad et al., 2024; Balistri et al., 2022).

4.3 Beer

Connected to beer, an IoT system for home brewing is studied (de Andrade et al., 2021), in (Hradecká, 2019) it is addressed how to make internal audit in industrial beer production with robotics and IoT, in (Knezevic and Kasunic, 2020) IoT is studied linked to a beer cooler and serving unit, while in (Afolaranmi et al., 2023) it is presented an IoT-AI system for monitoring tunnel pasteurization machines. In (Hradecká, 2019), IoT embedded robotics faces leakages, exceeding water and energy consumption, low sustainability, obsolescence of the plants, low system integration, difficult in receiving data. Maintenance is studied in (Knezevic and Kasunic, 2020), where the remote monitoring enables preventive maintenance, consumption control and units usage monitoring. The IoT system must meet a lot of requirements (Afolaranmi et al., 2023): flexible and easy solution, not invasive for the system, respectful of maximum quality of produced beer, able to monitor the system in real time, aiming to zero defect manufacturing with predictive quality, which has a current 92% accuracy.

5. Resilience 4.0 into beer production lines

This chapter explores in detail the impact of IoT, Edge, Fog, and Cloud Computing on the resilience of beer production lines, using a specific industrial case of a beer production facility, to illustrate how these technologies can be applied to enhance operational resilience.

5.1 IoT

Predictive Maintenance. IoT devices and data analysis enable failures predictions (Arena et al., 2022). In the brewery where the study was conducted, IoT sensors are installed on critical equipment such as pumps and valves in the brewing room. Sensors continuously monitor the conditions and detect signs of impending wear or malfunction. Temperature and vibration data enable maintenance team to predict failures, allowing proactive interventions that prevent production stoppages.

Operational adaptability. IoT devices can improve adaptability by collecting real-time data (Tian et al., 2024), like sales and consumption, indicating consumer preference trends. This data helps to adjust production schedules dynamically. For example, if there is a sudden increase in demand for a particular type of beer, the brewery can quickly ramp up production to meet market demands without overproducing less popular variants.

Crisis Management. In the event of a sudden failure in a fermentation tank, the IoT system immediately alerts the maintenance team and activates safety protocols to prevent product loss and further damage. This real-time alert system reduces the impact of failures and ensures a quick resolution of problems (Tian et al., 2024).

Quick Recovery. After a power outage, IoT-enabled energy management systems coordinate the sequential restoration of operations, prioritizing critical production lines to minimize downtime and maintain beer quality (Partovian et al., 2023).

Surveillance and Security. IoT cameras and motion sensors are strategically placed around sensitive areas like storage tanks and production zones. These devices detect unauthorized access or suspicious activities, sending immediate alerts to security personnel to protect resources and ensure operational continuity (Tian et al., 2024).

5.2 Edge Computing

Operational Continuity. During a cloud outage, the local Edge computing infrastructure at the brewery ensures that fermentation processes are continuously monitored and regulated. Local data processing at the Edge devices maintains production quality and efficiency even when the cloud connection is disrupted (Fogli et al., 2024).

Vulnerability Reduction. Edge computing units operate independently, safeguarding critical production processes from disruptions due to cyberattacks (Ahmad et al., 2024). For example, if an external attack targets the cloud infrastructure, the local Edge units continue to function, ensuring ongoing production.

Autonomous Emergency Management. Edge devices can make immediate on-site decisions during emergencies (Balistri et al., 2022). For instance, if a leak is detected in a beer tank, Edge systems automatically close the relevant valves and initiate emergency protocols without waiting for cloud-based commands.

Failure Point Reduction. If the internet connection fails, Edge systems continue to control and monitor operations such as temperature and pressure, ensuring uninterrupted production (Ahmad et al., 2024; Balistri et al., 2022).

Fast Recovery. It facilitates quick restoration of essential functions after interruption (Ahmad et al., 2024). After a power outage, Edge devices help restart production and synchronize data with the cloud once the connection is restored, minimizing resource waste and delays.

5.3 Fog Computing

Operational Flexibility. Fog computing enables distributed data management, enhancing IT infrastructure resilience (Kim et al., 2020). For instance, if a Fog node managing the refrigeration system fails, other nodes can immediately take over, ensuring continuous fermentation processes and maintaining beer quality.

Fast Recovery. Local Fog computing nodes, positioned near data collection points, facilitate quicker recovery from interruptions (Ahmad et al., 2024; Balistri et al., 2022). During a power outage, these nodes use backup power sources to resume operations swiftly, minimizing downtime on the bottling line.

Service Continuity. distributing data processing across multiple Fog nodes, the brewery reduces reliance on a single central data processing centre, increasing system resilience and operational continuity (Ahmad et al., 2024).

Quick Emergency Response. The proximity of Fog nodes to data collection devices allows for immediate responses to detected issues (Ahmad et al., 2024). For example, if sensors identify bacterial contamination during fermentation, Fog nodes quickly initiate sanitization protocols and alert personnel, safeguarding production batch.

Problem Isolation. Fog computing allows the isolation of problems to specific nodes or clusters, preventing a single point of failure from affecting the entire network (Ahmad et al., 2024). If a Fog node managing quality control data encounters an error, only that section of production is impacted, allowing other areas to remain operational.

5.4 Cloud Computing

Data Redundancy. Cloud computing ensures that vital data is backed up in multiple geographic locations (Ivanov and Yan, 2023). In case of a disaster at the brewery's main IT infrastructure, production data, beer recipes, and transaction records remain accessible from other sites, allowing for quick resumption of operations.

Resource Elasticity. The cloud provides the flexibility to scale IT resources up or down based on demand. During peak periods, such as holidays, the brewery can temporarily increase computing resources to handle increased sales and production volumes, ensuring continuous operations without over-investment in unused capacity (Fisher et al., 2020).

Business Continuity. Cloud services offer integrated disaster recovery solutions. Continuous cloud-based backups enable the brewery to quickly activate disaster recovery protocols, restoring critical functions almost instantly after a disruption (Chang et al., 2016).

Seamless Updates and Maintenance. Cloud-based production management systems receive automatic updates and maintenance without downtime, ensuring continuous availability and benefiting from the latest security and functionality enhancements (Corradi et al., 2022).

Advanced Security. Cloud providers implement advanced security measures, including data encryption, multi-factor authentication, and continuous threat monitoring, protecting sensitive information from cyberattacks and reducing the risk of data breaches (Yu et al., 2018).

5.5 Resilience 4.0 framework

Combining IoT, Edge, Fog, and Cloud technologies into a comprehensive Resilience 4.0 framework significantly enhances the overall resilience of the beer production line. This framework, showed in Appendix A, integrates data collection, local and distributed processing and centralized analysis to ensure continuous improvement and operational adaptability. This Resilience 4.0 framework aim to enable the brewery to adapt to changing customer preferences, quickly recover from disruptions, and maintain high operational efficiency and product quality. The integration of these technologies into the beer production line exemplifies the practical application of Industry 4.0 innovations, ensuring long-term resilience and business continuity.

Field Level: *Sensors:* sensors (temperature, pressure, vibration, etc.) are installed on key equipment such as fermentation tanks, pumps, and valves. they continuously monitor operational parameters and collect real-time data. *Actuators:* Devices that can control processes, such as adjusting temperature or pressure, based on sensor data to maintain optimal production conditions. *Machines Embedded with IIoT:* Industrial Internet of Things (IIoT) devices integrated into machinery enable connectivity and data sharing over the internet. *Data Transmission:* Collected data is transmitted over secure networks to local Edge and Fog nodes for initial processing.

Peripheral analysis: Edge Nodes: Localized computing devices that handle data processing close to the source. They perform real-time analysis, reduce latency, and manage data traffic efficiently. The benefits are immediate Response and better Data Cleaning. Edge nodes can quickly respond to data anomalies, such as triggering maintenance alerts if a sensor detects an out-of-range value. Moreover, initial data cleaning and filtering are performed to remove noise and ensure data quality. *Fog Nodes:* Intermediate computing devices that bridge the gap between Edge nodes and the Cloud. They aggregate data from multiple Edge nodes and perform further processing. The benefits are better resource management and latency reduction. Fog nodes manage resources efficiently, distributing computational tasks and ensuring continuous operation even if some nodes fail. By processing data closer to its source, Fog nodes significantly reduce the latency compared to centralized cloud processing.

Centralised analysis: Cloud Integration: Data from Fog nodes is aggregated and sent to the Cloud for comprehensive analysis. The benefits are advanced analytics, better data storage and real-time dashboards. The Cloud performs advanced data analytics, leveraging machine learning and big data tools to identify patterns, correlations, and insights that require a holistic view of the production process. The Cloud provides scalable storage solutions, ensuring that historical data is preserved and accessible for long-term analysis. Results from the Cloud analysis are displayed on real-time dashboards, accessible to management and operators for informed decision-making. *Predictive Insights:* Cloud analytics can predict maintenance needs, optimize production schedules and enhance product quality by analysing trends and forecasting future conditions. *Data Security:* Advanced security measures, including encryption and multi-factor authentication, are employed to protect sensitive production data from cyber threats.

Applied to beer production line, Resilience 4.0 can make the system a lot more flexible and adaptable to both internal and external requirements, like customer changes in the beer preferences. The system becomes faster in finding and recovering from adverse events, like problems in the production lines. Furthermore, this framework enables a higher business continuity as the structure based on Edge and Fog nodes is resilient itself, as problems, like even cyber-attacks, can be isolated, the spread of them is avoided, and the overall system can continue to operate in full efficiency. These characteristics leads to a better understanding of processes, better product quality and demand satisfaction. As beer is a perishable output and it suffers a lot from customers' requirements and tastes, an enhance resilience is vital for any brewer.

6. Results and Discussion

A **first result** is that Edge, Fog, Cloud and IoT can be perfectly integrated into a framework, enabling energy saving, data traffic and latency reduction, privacy and security improvements. Fundamental characteristics to enhance overall resilience. The **second and biggest result** is the integration of the 4 technologies into the beer production line, showing the great impact on resilience. IoT can provides the necessary data for predictive maintenance, operations adaptability to face crisis and quick recovery, and security. Edge and Fog provide first analysis and data cleaning, operations continuity and flexibility, the ability to face and isolate failures and crisis and to quick system restore. Cloud provides the final and complete insight, achieving redundancy, elasticity, continuity of the processes and better security.

7. Conclusions

Edge, Fog, and Cloud Computing can be successfully integrated together with IIoT to enhance the Resilience of a general production plant, in any field. This integration enables the creation of the framework Resilience 4.0, the new paradigm of resilience in the context of Industry 4.0. Resilience 4.0 can be successfully implemented in beer production lines, enhancing adaptability, flexibility, recovery speed, operations continuities, fault tolerance, problem isolation, security, and surveillance. This work has answered the 2 research questions and successfully solved the problem statement. This opens the way to new implementation studies about how importing the Resilience 4.0 into plants, not only of beer. A future work direction should be the extension of the authors' framework with other 4.0 technologies, like Digital Twin, Cyber Physical System (Lanzini et al., 2023) and Artificial Intelligence (Briatore and Revetria, 2022). KPI should be analysed, even if it is difficult to (Pinna et al., 2018).

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Appendix A. RESILIENCE 4.0 FRAMEWORK IN BEER PRODUCTION PLANT