The impact of new Technologies on resilience in Industrial Manufacturing: Smart Resilience framework

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This study aims to explore the potential of Industrial Internet of Things (IIoT), Digital Twins (DT) and Cyber Physical System (CPS) to enhance efficiency, productivity and resilience in the manufacturing industry and to examine how to integrate such technologies to develop a smart resilience framework based on technological architecture and processes, both designed, tested and generalized. Adopting IIOT, DT, and CPS offers several benefits, including the ability to respond promptly to unexpected and disruptive events, thereby improving the resilience of a productive manufacturing system. Through an in-depth literature analysis, the authors explored how the use of these technologies can help identify patterns to optimize production processes. This study highlighted how such technologies can be used to predict failures, optimize production and improve product quality, thus helping to strengthen the resilience of manufacturing companies. Furthermore, implementing an intelligent resilience framework not only improves operational efficiency, but prepares companies to face future challenges by increasing their ability to react to unexpected situations. Industry 4.0 (I4.0), with its advanced technologies, offers significant opportunities to improve resilience, especially in the manufacturing sector. The authors believe that the proposed framework can help manufacturing companies to change their approach from reactive to proactive, making them not only more effective in problem solving, but also more skilled in problem setting. Resilience, according to the authors, must not be seen in terms of the ability to recover from a harmful event, but also as the ability to anticipate it.

Keywords: IIoT, Digital Twin, Cyber Physical System, Resilience, manufacturing.

1. Introduction

Industry 4.0 (I4.0) is characterized by the introduction of various technologies such as IIoT, DT CPS, which emerge to address global challenges in terms of reliability, sustainability, and cost reduction (Agrawal et al., 2022; Fu et al., 2023; Javed et al., 2023; Sivakumar et al., 2024). I4.0 ensures rapid adaption to new products, processes, and applications with limited training data while preserving data privacy (Wang et al., 2022). This offers opportunities to smart and sustainable manufacturing (Konur et al., 2023). Implement I4.0 is a companies' need to remain competitive (Somohano-Rodríguez and Madrid-Guijarro, 2022). The effects include intelligent networks creation, autonomously controlled value chains, and highly flexible production (Trauer et al., 2021). The principles of I4.0 are interoperability, virtualization, decentralization, and flexible production. *Interoperability* is the ability to communicate by exchanging data and coordinating actions among machinery, computers, and people: IIoT is helpful in that (Givehchi et al., 2017). *Virtualization*, concerns the ability to generate virtual resources using data from sensors to replicate the real words, creating a CPS to build a DT, from which it receives data using IIoT to update itself (Eirinakis et al., 2022). The DT is very useful for real-time control of any machinery or plant and for simulating it to identify problems in advance, as well as for analyzing the capacity to manage potential orders. *Decentralization* indicates the transfer of system from the center of the edges of the company, thus enabling scalability (Agrawal et al., 2022). *Production flexibility* is the ability to address demand characterized by rapid changes and increasingly smaller production batches, moving towards mass customizations (Parri et al., 2021). Moreover, I4.0 has its value in healthcare, too (R. Mosca et al., 2022a). IoT, DT and CPS are the most impacting technologies for the data flow and analytics, and they are indeed the basis to create a more complete and evidence-based system. Following this author's perspective, this article aims to assess the impact of the above described 3 technologies on manufacturing companies' resilience. In manufacturing, I4.0 can provide great insight into the processes, enabling actions to prevent and mitigate potential disruption. The theme of resilience has indeed become crucial for companies' success (Lee et al., 2022). This is responsible for market instability, both from the demand and supply perspective, and requires companies to be resilient to changes in order to thrive (Eirinakis et al., 2022). However, this characteristic is almost not studied correlated to I4.0, on Scopus only 3,397 articles address these topics. Moreover, of the existing literature studied in the next chapter, only 10 papers present a framework for resilience connected to I4.0, showing clearly how little the research on this topic is currently. To solve this problem, it was divided into 3 research questions: 1) How IIoT, DT and CPS can impact on resilience? 2) How can these 3 technologies be integrated into a Smart Resilience framework? 3) What is the impact of this framework?

2. Literature Review

The first step of this research is the literature study based on Scopus database with the keyword strings of Table 1.

Table 1 – Strings of keywords

String	Explanation
IIoT OR DT OR CPS OR Cyber Physical System OR Digital Twin OR Industrial IIoT OR Industrial Internet of things OR Internet of Things OR IoT	Narrows the search to the technologies of interest
Resilien* OR Productivity OR Effectiveness OR Efficiency	Connects these technologies to the field of resilience
(Framework OR Roadmap OR Implementation OR Adoption) AND (Industry OR Manufactur*)	Focuses the research on their implementation in industry

4073 documents were initially found. To refine the search, strings were investigated using the "Keywords" filter in the search bar, resulting in 116 documents. Finally, only the 45 articles in English were selected for review. Therefore, there are 41 articles available for reading, of which 34 fall within the scope of the research. Moreover, a snowballing of 20 papers have been performed. Appendix A shows the PRISMA Model.
To better analyze the papers, the followed steps are:

1. Looking for the single technologies to understand how they treated them.
2. Comprehend how they can impact over resilience.
3. Looking for already existing frameworks and their potential and limitations.

IIoT is a network of interconnected devices, machines, sensors, and systems in industrial settings equipped with internet connectivity, enabling them to collect and exchange data (Han et al., 2021; Maleki et al., 2018; Shahzad et al., 2020; Sun et al., 2021; Vijayakumar and Shiny Angel, 2023). An increasing number of IIoT devices, as well as AI algorithms, are deployed to achieve industrial intelligence (Duan et al., 2020; Illa and Padhi, 2018; Zeng et al., 2019);. IIoT can increase visibility and awareness of energy consumption, a current topic (Bracco and Fresia, 2023), with smart sensors at the machine and production line levels (Jagtap et al., 2021; Karimanzira and Rauschenbach, 2019; Shrouf and Miragliotta, 2015; Zhu et al., 2022) across various of sectors (Qayyum et al., 2023). IIoT security is a key aspect to consider (Dong et al., 2019; Lupascu et al., 2020). **Resilience**: IIoT systems ensure resilience to production by minimizing disruptions, reducing downtime and maintaining consistent productivity levels (Shah et al., 2024).
DT is a dynamic representation of physical instances in a virtual environment continuously fed with data from sensors and software (Mohapatra and Bose, 2020). Its excellent state awareness and real-time analysis significantly aid decision-making and execution (Sun et al., 2021). DT implementation in manufacturing systems has shown great potential in enabling advanced manufacturing data management (Lanzini et al., 2023; Liu et al., 2022). **Resilience**: DT can enhance the resilience of production processes by enabling a manufacturing system to detect and to handle events that may disrupt production and to absorb and alleviate the corresponding consequences (Eirinakis et al., 2022).
CPS are physical and engineered systems whose operations are monitored, coordinated, controlled, and integrated by a computing and communication core (Barnwal et al., 2019; Gotzinger et al., 2020). These systems aim to implement autonomous and collaborative manufacturing objects and subsystems based on the context within and across all levels of production (Woo et al., 2018). CPS are worldwide advancing the industry to the next level (Givehchi et al., 2017). However, there is concern about cyber-attacks targeting critical systems, as industrial, medical, and energy ecosystems. Although the latest industry infrastructures heavily rely on AI-driven maintenance, prediction based on corrupted data undoubtedly results in loss of life and capital (Rahman et al., 2021). **Resilience**: CPS supports resilience by exploiting DT and failure models to improve operation, integration, maintenance, and recoverability for many application scenarios (Parri et al., 2021).
The combination CPS, IIoT and DT will make smart factories a reality (Ghodsian et al., 2023). As this technologies generate more and more data, new opportunities arise for companies, as they can monitor development and production processes, improve their products, and offer additional services (Trauer et al., 2021). Emerging paradigms of I4.0 expect CPS to reliably provide services overcoming disruptions in operative conditions and adapting to changes in architectural and functional requirements (Parri et al., 2021). This environment supports resilience in production, enabling manufacturing systems to identify and handle anomalies and disruptive events and supporting decisions to alleviate their consequences (Eirinakis et al., 2022). Furthermore, recent disruption, like COVID and wars, has revealed the vulnerability of modern manufacturing systems to endure disruptive changes; therefore there is a pressing need to improve manufacturing resilience (Lee et al., 2022).

3. Industry 4.0 technologies

Industrial Internet of Things (IIoT), Digital Twins (DT), and Cyber-Physical Systems (CPS), integration enhances resilience in manufacturing, transforming traditional manufacturing into intelligent ecosystems that can predict changes, adapt quickly, and learn continuously, enhancing overall productivity, resilience, and competitiveness. This section focuses on the impact of these technologies on resilience, providing examples to illustrate their benefits.

3.1 IIoT

IIoT facilitates the connectivity and interoperability of industrial devices, providing insights into operations. Data acquisition allows continuous monitoring and analysis of manufacturing processes (Olıverı et al., 2023), leading to optimized operational efficiencies and reduced downtime. Predictive and prescriptive maintenance are enabled, which can foresee equipment failures before they occur, substantially reducing unplanned outages and maintenance costs (Palacín et al., 2021), particularly useful when it comes to hazardous substances (Palacín et al., 2021) o biological (Roberto Mosca et al., 2022a, 2023a).

Resilience: The comprehensive environmental and operational parameters monitoring facilitates a holistic view of the manufacturing process, which results to be more resilient (Arena et al., 2021). This multi-variable data collection allows for accurate predictive and prescriptive maintenance (Arena et al., 2022), as the system can analyze correlations between different factors to predict potential failures more effectively. Vibration sensors on motors and bearings can predict wear and tear. If a machine is overheating, the system can alert maintenance teams and adjust operations to prevent a breakdown. This proactive approach minimizes downtime and ensures continuous production. By scheduling repairs during planned downtimes, the facility avoids unexpected breakdowns and production schedules changes, which would lead to delivery delays and customer trust loss.

3.2 Digital Twin

DTs are digital replicas of physical assets that provide real-time monitoring and simulation capabilities. A DT of a manufacturing plant can simulate different scenarios, such as a sudden spike in demand or a supply chain disruption. By testing various responses in the virtual model, manufacturers can identify the best strategies to mitigate risks without interrupting actual operations. This predictive capability allows companies to prepare for and adapt to disruptions effectively, enhancing their resilience.

Resilience: DTs play a vital role in scenario planning for potential disruptions. If a machine shows signs of failure, the DT can simulate the impact on production and explore rerouting operations strategies or modify production schedules. This proactive approach allows to maintain output levels and meet delivery commitments even when facing issues. The power of DTs is the integration of data from IIoT, creating a dynamic, real-time representation of the physical world. This integration enables multi-variable analysis, where the DT can simulate complex interactions between various factors, such as production speed, equipment health, and environmental conditions, optimizing processes, identifying potential bottlenecks, and developing robust contingency plans.

3.3 Cyber Physical Systems

CPS integrate digital and physical systems, enabling real-time data analysis and automated decision-making. If a CPS detects a quality issue in the production process, it can autonomously adjust machine settings to correct the problem while notifying human operators. This real-time adjustment ensures product quality and minimizes waste, contributing to a more resilient manufacturing process that can quickly adapt to changes with high performances.

Resilience: CPS enhances resilience by continuously monitoring health and performance of all connected components. If abnormalities are detected in a machine, the CPS alerts the maintenance team and take immediate steps to redistribute the load to other machines, maintaining production flow during equipment repair. This capability minimizes downtime and ensures that production targets are met consistently, even under adverse conditions. CPS benefit from the data provided by IIoT sensors and the predictive insights generated by DTs. This integration allows CPS to make informed decisions based on a comprehensive understanding of the manufacturing environment.

4. Smart Resilience Framework

This section outlines authors' Smart Resilience Framework, integrating IIoT, DT, and CPS to ensures that manufacturing systems are resilient, adaptive, and able to maintain high performance under varying conditions. In Appendix B, a schematic figure illustrates the different components of the framework and their relationships. Its development was heavily informed by the literature review, which highlighted the potential of IIoT, DT, and CPS to enhance resilience in manufacturing. By analyzing various studies and existing frameworks, key components and strategies were identified and adapted to create a comprehensive framework suitable for the manufacturing industry. While previous research in healthcare, as provided valuable insights into resilience strategies that can be applied to manufacturing. Healthcare systems often employ real-time monitoring, predictive analytics, and automated responses to manage patient care and operational efficiency. These principles are directly applicable to manufacturing, where similar technologies can be used to monitor equipment health, predict maintenance needs, and automate responses to disruptions (R. Mosca et al., 2022b; Roberto Mosca et al., 2022b). Same happens in warehouses (R. Mosca et al., 2022c, 2022d).

4.1 IIoT and connectivity

IIoT is the first layer of the framework, creating a network of connected devices and sensors. These devices continuously collect data on machine performance, environmental conditions, and production outputs. This real-time data is crucial for identifying anomalies early and reacting swiftly to prevent disruptions.

4.2 Digital Twins and prediction

DTs function as dynamic, predictive models that mirror physical processes. They evolve based on continuous feedback from IIoT sensors, enabling them to simulate different operational scenarios and predict outcomes under various conditions. DTs are essential for conducting 'what-if' analyses, assessing how the system would respond to potential disruptions such as equipment failure, supply chain delays, or sudden spikes in demand. This predictive capability is crucial for testing and generalizing the resilience framework.

4.3 CPS and Automated Decision-Making

CPS integrates IIoT and DTs capabilities, embedding intelligence into physical assets. Autonomous decision-making is facilitated, as CPS can initiate corrective actions without human intervention, based on predefined criteria and real-time data insights. If a machine component shows signs of wear, CPS can automatically schedule maintenance or reroute tasks to other machines, ensuring uninterrupted production. This level of automation and self-regulation is critical for a resilience framework that responds and adapts to current conditions.

4.4 Implementation and Generalization

The final stages involve rigorous testing and generalization of the technological architecture. This process includes simulating extreme conditions to ensure the system can cope with potential crises and integrating feedback loops to refine the response mechanisms. Generalization involves scaling the solutions to different parts of the manufacturing process and potentially to other factories or geographic locations, ensuring that the resilience framework is robust, adaptable, and transferable across various manufacturing scenarios.

5. Smart Resilience framework: potential application

The automotive manufacturing sector was chosen to illustrate the application of the Smart Resilience Framework due to its complex supply chains, high automation levels, and critical need for operational resilience. Automotive manufacturing involves intricate processes, numerous interdependent systems, and significant global supply chain dependencies, making it an ideal candidate to demonstrate the efficacy of the Framework in a real-world setting. The Framework application in an automotive manufacturing plant, therefore, demonstrates its potential to enhance operational resilience. By integrating IIoT, DT, and CPS, manufacturers can have continuous production, maintain high product quality, and quickly adapt to changes, ensuring long-term sustainability and competitiveness. Here is how the framework can be applied:

IIoT Deployment and Data Collection: Sensors are installed on assembly line robots, paint shop equipment, and stamping machines to collect real-time data on various operational metrics such as speed, temperature, pressure, and output quality. This data is continuously monitored to detect any deviations from normal performance that could indicate potential problems. If IIoT sensors detect an anomaly such as overheating in a stamping machine, the system can automatically alert maintenance teams and adjust operations to prevent a breakdown. This proactive approach minimizes downtime and ensures continuous production.

Digital Twins Integration and Scenario Simulation: Each critical component of the manufacturing process, from the assembly line to logistics, is replicated in a DT model. A DT of the paint shop can simulate various environmental and chemical parameters to predict the quality of paint application under different conditions. By conducting 'what-if' analyses, manufacturers can assess how the system would respond to potential disruptions such as equipment failure, supply chain delays, or sudden spikes in demand. This predictive capability allows for preemptive adjustments to avoid defects and maintain high product quality.

Cyber-Physical Systems Implementation and Automated Decision-Making: During typical operations, if IIoT sensors detect an unexpected slowdown in the assembly line due to a robotic arm malfunction, the CPS quickly assesses whether to reroute tasks to other robots or slow down upstream processes to avoid bottlenecks. Simultaneously, the assembly line DT runs a simulation to verify if the adjustments will maintain production efficiency, without compromising safety or product quality (R. Mosca et al., 2023a). Maintenance teams are alerted automatically with detailed diagnostic information, ensuring that the malfunctioning is addressed promptly.

The integration of IIoT, DT, and CPS in the Smart Resilience Framework offers several key benefits:

Real-Time Monitoring and Maintenance: Continuous data collection and analysis allow for the early detection of potential issues, enabling predictive and prescriptive maintenance and reducing unplanned downtime.

Predictive Analysis and Scenario Planning: DTs provide valuable insights through simulation, allowing manufacturers to prepare for and adapt to disruptions effectively. This capability enhances the plant's ability to maintain production continuity.

Autonomous Decision-Making and Rapid Response: CPS enable real-time adjustments to operations, ensuring stability and continuity. Autonomous decision-making reduces the need for human intervention, allowing for faster and more efficient responses to disruptions.

Enhanced Operational Resilience: By combining real-time monitoring, predictive analysis, and automated decision-making, the framework creates a resilient manufacturing environment capable of withstanding and recovering from disruptions.

6. Results

In Table 2 are shown the results of our research.

Table 2 - Results

N°	Explanation
1	The literature clearly states that I4.0 is a paradigm which can improve undeniably resilience and sustainability

2	The single technologies, even if taken singularly, can provide a better resilience
3	The integration of IIoT, DTs and CPS makes possible a new level of resilience as they cooperate for a better knowledge of the systems
4	The Smart Resilience framework proposed, being based on DTs, enables the system to test and optimize itself with scenario simulation. Activity fundamental as stress test is the basis to understand if the system can face or not real disruption
5	The Smart Resilience framework also enables a higher sustainability. Then there is a clear connection between these resilience and sustainability

I4.0 adoption can be a great bust towards a more resilient and sustainable system. In the resilience domain, IoT, DT and CPS can provide great value with real time monitoring, adverse event forecasting, and disruption mitigation with quick and precise intervention. When integrated into a Smart Resilience framework, these 3 technologies can bring an even higher resilience. This framework can test the system with scenario simulations based on real conditions, measured in real-time, and improve it. Finally, it was shown also that this kind of integration will achieve great benefits in the domain of sustainability. This last result is a clear sign that resilience and sustainability are correlated and improving the first will bring enhancement in the latter, too.

7. Discussion and Conclusions

I4.0 can improve the resilience of plants in any field as it improves the knowledge of the systems. The creation of a Smart Resilience framework is then a need and an opportunity to reach a new level of adaptability, flexibility, and resilience. Authors' solution can provide a strategic advantage by enhancing the ability to anticipate, respond to and recover from disruptions swiftly and efficiently, resulting in more resilient industrial plants. The continuous learning capabilities of the proposed solution will improve this characteristic, making the system capable of handling complex scenarios with greater agility and less human oversight. The results of this paper show the importance of continuing to work on the connection between I4.0 and resilience, in all fields. In this paper, only IIoT, DTs and CPS have been considered as the basis for future implementations of even higher impact. Future research directions should in fact include also other 4.0 technologies, like Big Data and Artificial Intelligence, getting great benefits as shown in (Briatore et al., 2023; Briatore and Revetria, 2022; Famoso et al., 2024). The proposed framework, before being expanded with AI and Big Data integration, must be validated with a real case study or simulation, to overcome current limitations. A special focus on sustainability should be carefully analyzed, as a company should analyze it's overall strategy considering this aspect, too (Pinna et al., 2018; Tonelli et al., 2016) and climate change is a very current topic (Demartini et al., 2023; Fresia and Bracco, 2023). In this field, energy consumption will be very important (Chinese et al., 2022; Fresia et al., 2024). The relations between sustainability and resilience should be addressed, to create more complete frameworks. In fact, a more resilient system leads to less reworks and emissions and then the overall impact on environment is reduced. Finally, human-centric view will be addressed, especially about safety of every kind of worker (R. Mosca et al., 2023b; Roberto Mosca et al., 2023b; Peron et al., 2022). This final topic must be considered as I4.0 should not just be considered on the technological side. In fact, the knowledge that is created is to serve humans and not to substitute them, improving their resilience as better informed.

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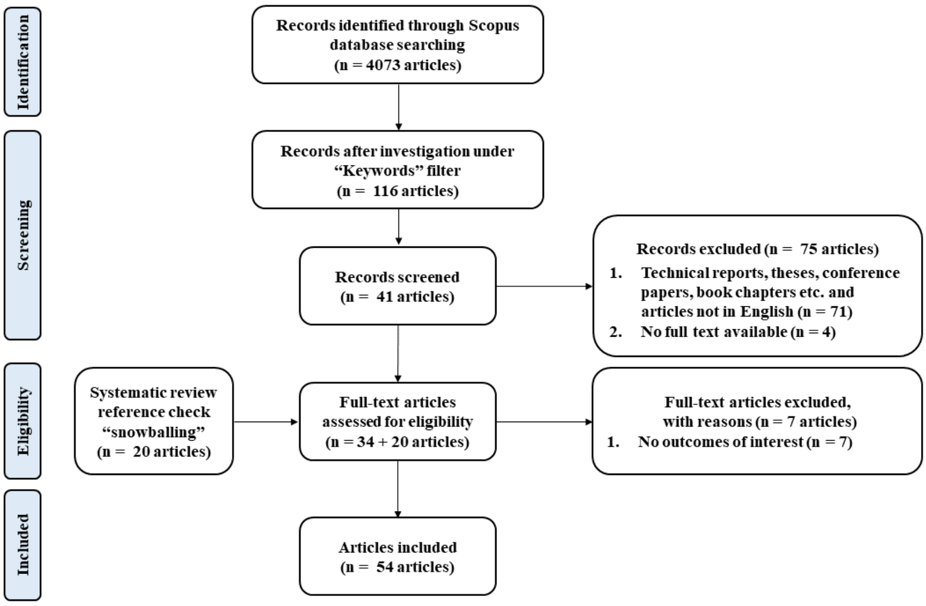
Appendix A. PRISMA SCHEME



Appendix B. SMART RESILIENCE FRAMEWORK