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Developing Adaptive and Resilient Manufacturing Systems Through Smart Technology Integration

Masingita Onica Mohlala and Ngaka Mosia
Industrial Engineering and Engineering Management
School of Engineering and the Built Environment
University of South Africa
Florida, South Africa
mohlamo@unisa.ac.za, mosian@unisa.ac.za

Abstract

This study responds to the growing need for manufacturing systems that can adapt and remain resilient in the face of increasing complexity and ongoing global disruptions. It presents a structured framework that shows how smart technologies can be used to strengthen manufacturing systems. Unlike traditional approaches that focus mainly on improving productivity, this study places equal emphasis on building systems that are both adaptable and resilient. To achieve this, the study uses a qualitative and conceptual approach, drawing on existing literature and documented industry practices. The findings indicate that when smart technologies are effectively integrated, they can improve operational efficiency, support better real-time decision-making, and reduce process variability, while also making systems more flexible and responsive to change. The main contribution of the study is the development of a clear and structured framework for smart manufacturing resilience. This framework connects technology integration with key system capabilities such as flexibility, responsiveness, and robustness. It also offers practical guidance for organisations looking to move from traditional manufacturing methods to more intelligent, adaptive, and resilient production systems.

Keywords
Smart manufacturing, Industry 5.0, resilience, IoT, digital transformation.

1. Introduction
The development of adaptive and resilient manufacturing systems is increasingly supported by advanced digital technologies such as cyber-physical systems (CPS), the Internet of Things (IoT), artificial intelligence (AI), and digital twin models. These technologies enable seamless real-time data exchange across production environments, allowing systems to monitor operations continuously and respond dynamically to disruptions (Romero and Stahre 2021). Through predictive analytics and intelligent control mechanisms, manufacturing systems can anticipate potential failures, optimize performance, and self-adjust in response to changing conditions.

In addition, modern manufacturing approaches emphasize human-centric design principles, often referred to as Industry 5.0. In this context, operators work alongside intelligent systems, enhancing decision-making, flexibility, and system recovery during disruptive events such as supply chain interruptions or global crises (Tóth et al. 2023). The concept of a "resilient operator" highlights the importance of integrating human expertise with digital capabilities to achieve sustainable and adaptable production systems. To support these advancements, structured frameworks based on modular system architectures are increasingly adopted. These frameworks enable scalability, interoperability, and effective risk management across different operational levels, including enterprise-wide (macro), process-level (meso), and machine-level (micro) systems (Sheth and Kusiak 2022).

Empirical studies indicate that the integration of smart technologies can lead to measurable improvements in manufacturing performance, including increased throughput and reduced downtime. Furthermore, digital twin technologies allow organizations to simulate and evaluate potential disruptions in a virtual environment, supporting proactive decision-making and system optimization (Banerjee et al. 2024). Despite these benefits, challenges such as cybersecurity risks, integration with legacy systems, and workforce readiness remain critical considerations in the successful implementation of smart manufacturing solutions.

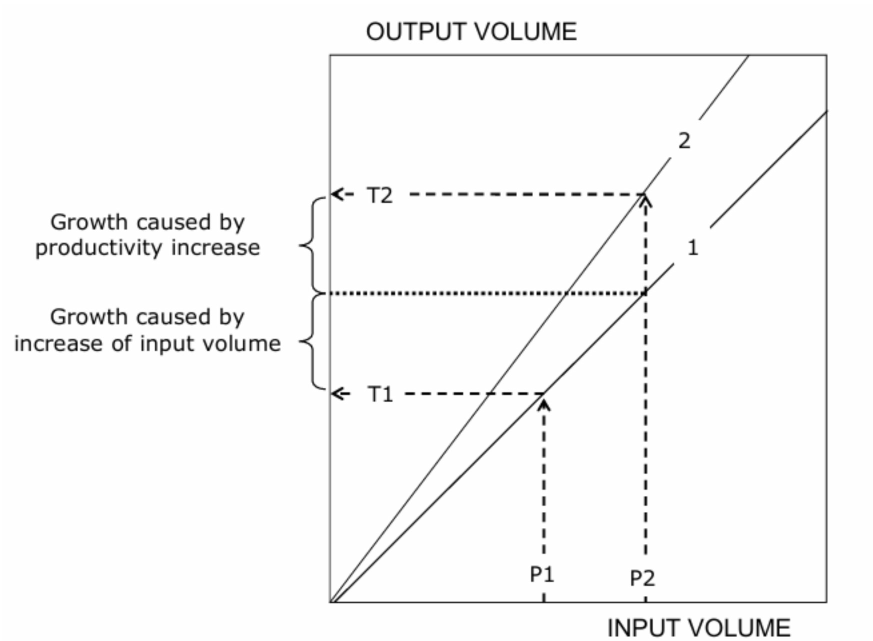

Figure 1. Input-Driven vs Productivity-Driven Growth in Manufacturing Systems
(source: Saari 2006)

From a production perspective, improvements in manufacturing performance can be achieved through either increased resource input or enhanced productivity. As illustrated in Figure 1, output growth resulting from increased input volume is often limited by cost, resource availability, and operational constraints. In contrast, productivity-driven growth allows manufacturing systems to achieve higher output levels without a proportional increase in inputs. In the context of smart manufacturing, the integration of advanced technologies such as IoT, AI, and digital twins plays a critical role in enabling productivity-driven improvements. These technologies enhance process efficiency, reduce non-value-adding activities, and support real-time decision-making, thereby allowing manufacturing systems to operate more effectively under dynamic conditions. As a result, technology-enabled productivity improvements not only increase output but also contribute to the development of more adaptive and resilient manufacturing systems.

This concept is further supported by Figure 2, which illustrates the impact of technological advancement on production performance. The upward shift from F_0 to F_1 represents an increase in output resulting from improvements in technology and process efficiency rather than additional resource input. In modern manufacturing environments, the integration of smart technologies such as IoT, artificial intelligence, and cyber-physical systems enables this shift by enhancing real-time monitoring, optimizing processes, and supporting predictive decision-making.

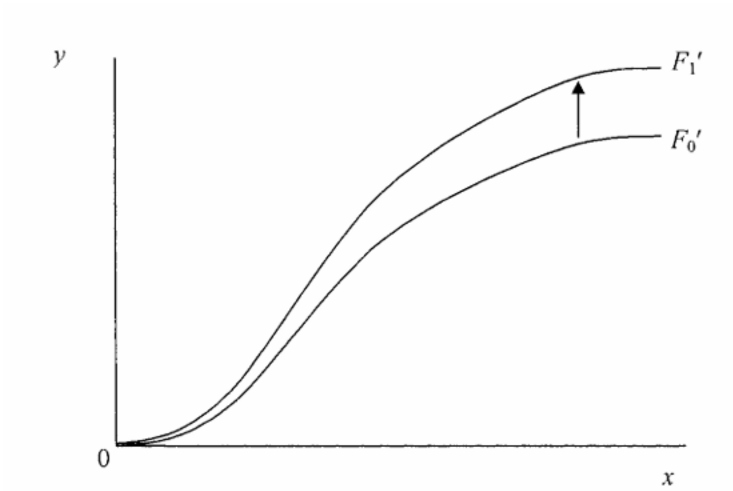

Figure 2.Impact of Technological Innovation on Manufacturing Output (source: Coelli et al. 2005)

Together, these perspectives highlight the transition from traditional input-driven manufacturing systems toward technology-enabled, productivity-driven models. This transition is essential for developing adaptive and resilient manufacturing systems capable of maintaining performance under dynamic and uncertain conditions.

This study aims to examine how smart technologies can be applied to improve manufacturing system resilience. The objective is to provide a practical understanding of how digital tools can support adaptive and efficient production systems in modern industrial contexts. It seeks to examine the limitations of traditional manufacturing systems and explore how digital technologies can enhance system performance. It further aims to identify effective strategies for integrating smart technologies into manufacturing processes. Ultimately, the research intends to develop a structured approach to improving system resilience in modern manufacturing environments.

This study adds to existing research by bringing together key ideas that are often treated separately such as productivity, adaptability, and resilience in manufacturing systems. While earlier studies tend to focus on these aspects individually, this work connects them through a structured framework that shows how smart technologies can support more resilient and responsive systems. It also takes a human-centred approach in line with Industry 5.0, emphasising the importance of collaboration between people and technology in improving overall system performance. By combining these perspectives, the study offers a more complete view of how manufacturing systems can evolve into adaptive and resilient environments.

2. Literature Review

Research on smart manufacturing and Industry 4.0 consistently highlights how technologies such as the IoT, AI, and CPS are transforming traditional production environments into highly connected and intelligent systems. These integrated systems are widely reported to improve both resilience and productivity, with some studies showing operational efficiency gains of up to 20% through the use of digital twins and real-time data analytics (Büchi et al. 2020). A key focus in this field is manufacturing resilience, which is increasingly achieved through adaptive systems capable of responding to disruptions such as supply chain breakdowns (Elhabashy et al. 2021). This is often supported by AI-driven predictive maintenance and modular system designs that allow quick adjustment to changing conditions. Interest in these approaches has grown significantly since 2018, reflecting a clear shift toward more flexible and responsive manufacturing models (Elhabashy et al. 2021). More recent discussions also extend into Industry 5.0, where the emphasis shifts from full automation to collaboration between humans and machines. In this context, smart technologies are not only improving performance, by approximately 15–30% in some case studies but also supporting a more human-centred approach that values worker well-being alongside productivity and sustainability (Peruzzini et al. 2024).

Smart Manufacturing, Industry 4.0, and Resilience
Smart manufacturing in Industry 4.0 uses CPS and the IoT to build more resilient production environments that can respond quickly to disruptions such as equipment failures. These technologies enable real-time monitoring and faster decision-making, helping organizations reduce risks across the entire value chain (Gangmei and Dutta 2023). In many cases, digital frameworks also incorporate digital twins, which allow manufacturers to simulate scenarios and plan recovery strategies more effectively, leading to reported downtime reductions of about 15-22% in high-tech industries (Elhabashy et al. 2021). More recent developments are moving toward Industry 5.0, where the focus is shifting to human-centric smart manufacturing. This approach combines advanced technologies like AI and IoT with human input to create more sustainable and adaptive systems. Systematic reviews show that these technologies, when well-integrated, strengthen both system resilience and sustainability (Zhang et al. 2023). Empirical studies further indicate that the depth and breadth of technology adoption in smart factories significantly improve performance and create new opportunities, particularly for smaller production units.

Smart Technologies and Productivity
Smart technologies such as AI and digital twins are playing an increasingly important role in improving productivity by streamlining processes and enabling better decision-making. In the context of Industry 5.0, the collaboration between humans and AI is especially important, as it enhances both operational efficiency and product quality, with some prototype systems achieving efficiency levels above 90% (Peruzzini et al. 2024). In addition, Lean 4.0 tools like digital poka-yoke are helping industries reduce defects and improve process capability, with reported improvements in Cpk values from 1.278 to 2.0, while also contributing to cost savings and even the creation of new job opportunities (Rahardjo et al. 2023). Recent frameworks for smart manufacturing emphasize a more balanced approach that integrates productivity with worker well-being, using adaptive systems that support human–technology collaboration on the factory floor. Case studies in Industry 4.0 environments, such as those applying DMAIC within lean manufacturing systems, have demonstrated significant performance improvements, including achieving near 100% production efficiency and substantial cost savings. In sectors like semiconductors, smart manufacturing ecosystems powered by real-time AI are further enhancing capacity planning and quality control (Rahardjo et al. 2023).

Human-Centric Manufacturing, Industry 5.0 and Challenges
Industry 5.0 represents a shift away from purely technology-driven manufacturing toward a more human-centric approach, where people and machines work closely together through advanced human-machine interaction (HMI) (Zhang et al. 2023). This approach builds on lessons from Industry 4.0 by addressing earlier gaps related to worker well-being, using co-evolution models that balance automation with human needs and promote both productivity and sustainability. At the same time, smart sensors and data-driven systems are being designed not only to improve efficiency but also to support safer and more comfortable working environments. Despite these benefits, the transition to Industry 5.0 is not without challenges. Many organisations face high implementation costs, shortages of skilled workers, and growing cybersecurity concerns. Studies suggest that around 60–70% of firms still struggle with interoperability issues when trying to integrate different smart systems (Frere et al. 2028).

Resilience Mechanisms and Adaptivity
Resilience in smart manufacturing is increasingly achieved through adaptive planning and self-organizing systems that can quickly adjust operations when disruptions occur. Rather than relying on fixed schedules, modern systems use simulation tools and AI-driven controls to dynamically reschedule processes in response to failures or unexpected changes (Tran et al. 2019). This adaptability is further strengthened through advanced techniques such as subgroup analysis for risk stratification and digital twin, based cyber-attack detection, which help distinguish normal operational anomalies from genuine threats, even during unstable or transitional system states (Fowler et al. 2023). In the context of Industry 5.0, AI-orchestrated cyber-physical systems (CPS) play a central role, significantly influencing sustainability and resilience outcomes, with studies indicating that they may account for around 59–64% of these effects, depending on organizational readiness and capability (Shofiullah 2025)

From a broader perspective, resilience in smart manufacturing integrates macro-, meso-, and micro-level factors, combining digital technologies with organisational processes to enable faster disruption recovery (Fowler et al. 2023). This is supported by an adaptive system-of-systems approach, where modular robotics and intelligent planning allow production systems to reorganize and reschedule tasks on the fly (Weichhart et al.2021). Empirical findings also show that AI-orchestrated CPS can strongly predict resilience outcomes, with regression effects reported in the range of β= 0.54-0.62 through real-time coordination mechanisms (Shofiullah 2025). These approaches promote more ecological, efficient, and disruption-tolerant manufacturing environments. However, most evidence currently comes from simulation studies and prototypes, meaning that large-scale industrial validation is still limited.

Although significant research has been conducted on smart manufacturing and digital transformation, there is still a need for structured approaches that integrate these technologies to enhance manufacturing resilience. This study addresses this gap by examining how smart technologies can be applied to improve adaptability and operational performance in manufacturing systems.

Case Studies and Applications

Early-stage prototypes show how digital technologies are already being applied in real industrial settings such as biopharmaceutical production and electronics manufacturing. In these cases, hybrid control systems help maintain product quality, for example, by reducing turbidity variations to below 5% through precise acoustic power adjustments (Banerjee et al. 2024). Similarly, in additive manufacturing and drilling operations, cyber-physical systems integrated with digital twins are being used not only to optimise workflows but also to detect cyber-attacks and operational anomalies. These improvements have been linked to reductions in production defects of around 15%, showing clear potential for smarter and more secure manufacturing processes (Ryalat et al. 2023).

In developing economies such as Indonesia, early adoption of smart manufacturing technologies is also emerging, particularly through AI and IoT integration. These systems are beginning to improve operational efficiency, although progress is often constrained by infrastructure limitations and skills shortages (Safarudin 2025). Overall, developing CPS–DT systems for bioprocessing has demonstrated high efficiency levels, achieving over 90% performance in CHO cell separation through dynamic control system updates (Banerjee et al. 2024). At the same time, digital twin based cyber-attack detection has been successfully tested in environments such as 3D printing, where it helps distinguish between normal operational variations and genuine threats (Balta et al. 2023). Together, these examples highlight promising but still early-stage applications of smart manufacturing, where real-world validation is ongoing and uneven across sectors and regions.

Integrating smart technologies such as CPS, the IoT, AI, and digital twins is proving to be a strong foundation for building more adaptive and resilient manufacturing systems. Much of the current evidence shows the clearest benefits in real-time responsiveness and improved risk management, where systems can quickly adjust to disruptions and reduce potential failures (Fowler et al. 2023; Safarudin 2025). However, there are still areas that are not fully understood, especially when it comes to how humans interact with these advanced systems on a large scale. This part still needs more real-world testing and validation. Even so, early findings suggest that improvements in efficiency of around 15-22% are possible when these technologies are properly implemented (Ryalat et al. 2023).

Overall, Industry 4.0 and 5.0 approaches are increasingly seen as practical solutions for managing complex and fast-changing production environments. A key takeaway is that modular and flexible system designs are essential, as they allow manufacturing operations to remain stable, responsive, and resilient over time (Weichhart et al.2021).

3. Research Methods

This study uses a qualitative research approach to explore how smart technologies can support the development of adaptive and resilient manufacturing systems. It is conceptual in nature and draws on existing literature as well as documented industrial practices rather than collecting primary data. This approach is suitable because it allows for a deeper understanding of complex issues such as technology integration, system adaptability, and resilience in manufacturing environments. The research follows a conceptual and analytical design, focusing on interpreting and synthesising existing knowledge to identify key themes, patterns, and relationships within the field of smart manufacturing. Through this process, the study develops a clearer understanding of how digital technologies contribute to improving manufacturing performance and enhancing system flexibility.

The study is based on secondary data sources, including peer-reviewed journal articles, conference proceedings, industry reports, and technical documents. These sources provide valuable insights into the use of technologies such as the IoT, artificial intelligence, cyber-physical systems, and digital twins within modern manufacturing settings.
The collected literature was analysed using a thematic analysis approach. Relevant studies were reviewed, grouped, and organised into key themes such as technological integration, productivity improvement, system adaptability, and

resilience. By examining patterns and relationships across these themes, the study develops a coherent understanding of the impact of smart technologies on manufacturing systems. Based on this analysis, a conceptual framework was developed to illustrate how smart technologies contribute to enhancing manufacturing resilience. The framework brings together the key technological and operational elements identified in the literature and provides a structured way of understanding how traditional manufacturing systems can evolve into more adaptive, intelligent, and resilient smart manufacturing environments.

4. Results and Discussion

4.1 Results

Analytical findings

The analysis of existing literature and documented manufacturing practices reveals that the integration of smart technologies plays a significant role in enhancing the adaptability and resilience of manufacturing systems. The findings indicate that improvements in system performance are not solely driven by increased resource input but are largely influenced by the effective implementation of digital technologies. Smart manufacturing technologies, including automation, IoT, AI, and cyber-physical systems, contribute to improved process efficiency by reducing non-value-adding activities, minimizing delays, and optimizing resource utilization. These improvements enable manufacturing systems to operate more efficiently while maintaining flexibility in responding to changing operational conditions.

A key observation from the analysis is that process optimization, supported by technological integration, leads to reduced process complexity and improved workflow coordination. This enhances the system's ability to respond to disruptions, thereby strengthening its resilience. For example, real-time monitoring enabled by IoT devices allows for immediate detection of process deviations, while AI-driven analytics support predictive decision-making, reducing the likelihood of unexpected system failures. The findings further suggest that productivity improvement in modern manufacturing systems should be viewed within the broader context of resilience. While traditional approaches to productivity focus on increasing output, smart manufacturing emphasizes the ability to sustain performance under dynamic and uncertain conditions. In this regard, improvements in efficiency, reduced cycle times, and optimized resource utilization contribute to both higher productivity and enhanced system resilience.

The transition from input-driven growth to technology-enabled productivity highlights the importance of innovation in manufacturing systems. The integration of smart technologies enables systems to achieve higher output levels without increasing resource consumption, thereby supporting sustainable and adaptive production environments.

The analysis indicates that smart technology integration is a critical enabler of resilient manufacturing systems, as it enhances operational efficiency, supports real-time decision-making, and improves the ability of the system to adapt to disruptions.

Smart Technology Strategies for Enhancing Resilience

Based on the thematic analysis, several smart technology strategies have been identified as key enablers of manufacturing system resilience. These technologies address common inefficiencies in traditional manufacturing systems while supporting adaptive and intelligent production processes.

- Internet of Things (IoT) and Real-Time Monitoring: The deployment of IoT sensors enables continuous monitoring of machine performance, production activities, and environmental conditions. This enhances operational visibility and allows for early detection of inefficiencies and system disruptions.
- Predictive Analytics and Artificial Intelligence: AI-driven analytics enable manufacturing systems to predict equipment failures, optimize production schedules, and respond proactively to potential disruptions. This reduces downtime and improves system reliability.
- Automation and Robotics: The use of automated systems and robotics improves operational consistency, reduces manual intervention, and enhances production speed. This contributes to improved efficiency and supports system stability under varying conditions.
- Digital Twin Technology: Digital twins provide virtual representations of manufacturing systems, allowing for simulation and testing of process changes without disrupting actual operations. This enables proactive identification of inefficiencies and supports informed decision-making.

- Cloud Computing and Smart ERP Systems: Cloud-based systems enable centralized data management, real-time information sharing, and improved coordination across different production units. This enhances flexibility and supports scalable operations.
- Additive Manufacturing and Flexible Production Systems: The use of additive manufacturing technologies supports rapid prototyping and flexible production, enabling manufacturing systems to adapt quickly to changing demands.
- Augmented Reality (AR) for Training and Maintenance: AR technologies support workforce development by providing real-time guidance during maintenance and operational tasks, reducing downtime and improving system responsiveness.

These strategies collectively contribute to the development of manufacturing systems that are not only efficient but also adaptable and resilient in the face of operational uncertainties.

4.2 Discussion

The findings of this study highlight the critical role of smart technology integration in transforming traditional manufacturing systems into adaptive and resilient production environments. The results indicate that while conventional manufacturing approaches focus primarily on efficiency and output, modern systems must also prioritize adaptability and responsiveness to remain competitive in dynamic environments. The integration of smart technologies enables manufacturing systems to move beyond reactive operations toward proactive and predictive management. For instance, the use of IoT and AI technologies allows organizations to monitor system performance in real time and anticipate potential disruptions before they occur. This capability significantly enhances the resilience of manufacturing systems by reducing vulnerability to unexpected failures and operational delays.

Furthermore, the study emphasizes that improvements in efficiency are closely linked to resilience. By reducing non-value-adding activities and optimizing resource utilization, manufacturing systems become more robust and capable of maintaining performance under varying conditions. In this context, productivity improvement should not be viewed in isolation but as a component of a broader resilience strategy. The discussion also highlights the importance of human–technology interaction in achieving resilient manufacturing systems. As emphasized in Industry 5.0, the collaboration between human operators and intelligent systems enhances decision-making, flexibility, and system recovery. This human-centric approach ensures that technological advancements are effectively utilized to support operational adaptability.

Despite the significant benefits of smart technology integration, several challenges remain. These include cybersecurity risks, integration with legacy systems, and the need for workforce upskilling. Addressing these challenges is essential for the successful implementation of resilient manufacturing systems. Overall, the study demonstrates that the integration of smart technologies provides a pathway for developing manufacturing systems that are not only efficient but also capable of adapting to disruptions and sustaining performance in complex environments. Based on the thematic analysis conducted in this study, recurring patterns were identified across the literature relating to smart technology integration, process optimization, system adaptability, and resilience outcomes. These themes revealed strong interconnections between digital technologies, operational processes, and system-level capabilities. To synthesise these findings into a structured representation, a conceptual framework was developed. The framework integrates the key elements identified during the analysis and illustrates how smart technologies contribute to enhancing manufacturing resilience. It reflects the relationships between technological enablers, core manufacturing processes, governance mechanisms, and resulting system capabilities. The proposed framework therefore represents a consolidation of the analytical findings and provides a holistic view of how adaptive and resilient manufacturing systems can be achieved through smart technology integration.

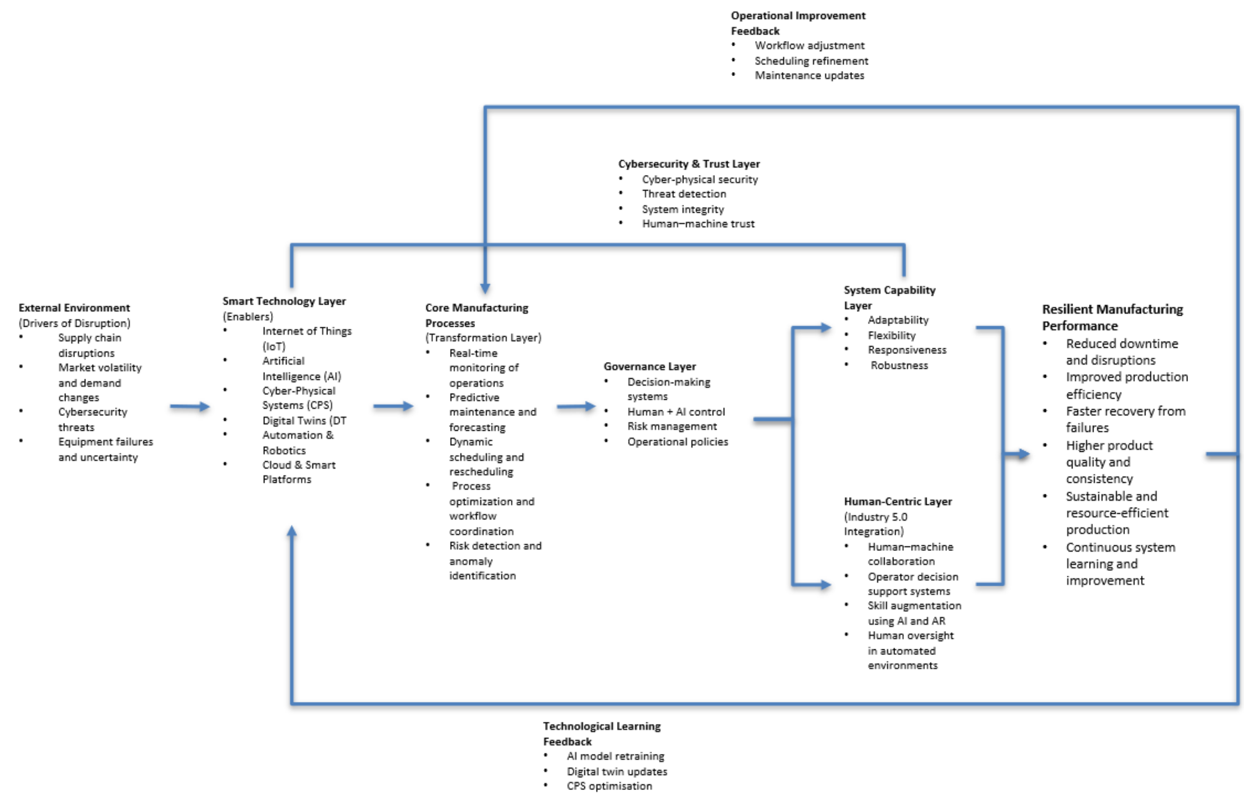

Figure 3. Proposed Smart Manufacturing resilience framework

Figure 3 illustrates the Smart Manufacturing Resilience Framework, which presents a structured view of how digital technologies enable the development of adaptive and resilient manufacturing systems. The framework begins with the external environment, where factors such as supply chain disruptions, market volatility, equipment failures, and cybersecurity threats influence manufacturing operations. To respond to these challenges, a Smart Technology Layer is introduced, consisting of enabling technologies such as the IoT, AI, CPS, digital twins, and cloud-based platforms. These technologies support real-time data acquisition, predictive analytics, and system connectivity, forming the foundation for intelligent manufacturing processes. The Core Manufacturing Processes layer represents operational activities that are enhanced through digital technologies, including real-time monitoring, predictive maintenance, scheduling, and workflow optimization. These processes are supported by a Governance Layer, which ensures effective decision-making, risk management, and alignment between human operators and automated systems.

A Cybersecurity and Trust Layer spans across the framework, ensuring secure data exchange, system integrity, and reliable human–machine interaction. This layer is critical for protecting digital infrastructure and maintaining trust in increasingly interconnected manufacturing environments. The framework further highlights System Capabilities, including adaptability, flexibility, responsiveness, and robustness, which are essential attributes of resilient manufacturing systems. In parallel, the Human-Centric Layer emphasizes the role of human–machine collaboration, operator involvement, and continuous skill development, as advocated in Industry 5.0. These combined elements lead to Resilient Manufacturing Outcomes, such as reduced downtime, improved production efficiency, faster recovery from disruptions, enhanced product quality, and sustainable, resource-efficient operations. Overall, the framework demonstrates how the integration of smart technologies, supported by governance and cybersecurity, enables manufacturing systems to operate effectively in dynamic and uncertain environments.

Ultimately, the development of these capabilities leads to resilient manufacturing outcomes, including reduced operational disruptions, sustained system performance, and improved efficiency. The framework highlights the critical role of smart technology integration in enabling manufacturing systems to operate effectively in dynamic and uncertain environments. This framework serves as the primary contribution of the study.

5. Conclusion

This study examined how smart technology integration can support the development of adaptive and resilient manufacturing systems. The findings show that technologies such as the Internet of Things (IoT), artificial intelligence, cyber-physical systems, and digital twins can significantly improve manufacturing performance by increasing efficiency, enabling real-time decision-making, and supporting more proactive management of production systems. A key contribution of this work is the development of a structured conceptual framework that connects smart technology integration with important system capabilities such as adaptability, flexibility, and resilience. The study also highlights the need for modern manufacturing systems to move beyond a narrow focus on productivity and instead adopt more balanced approaches that emphasise responsiveness and robustness in dynamic and uncertain environments.

The results further underline the importance of human–technology collaboration, particularly in the context of Industry 5.0, where human-centred design plays an important role in improving both system performance and sustainability. At the same time, the study acknowledges ongoing challenges such as integration complexity, cybersecurity risks, and shortages of skilled workers, which continue to limit full implementation.

This research is limited by its conceptual nature and reliance on secondary data sources. As a result, future studies should focus on testing and validating the proposed framework through empirical research, such as case studies and real industrial applications, especially within small and medium-sized enterprises. Further work is also needed to develop standardised integration approaches and ethical guidelines for effective human–AI collaboration in manufacturing environments. Overall, the study provides both a practical and theoretical foundation for organisations aiming to transition towards more intelligent, adaptive, and resilient manufacturing systems.

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Biographies

Masingita Onica Mohlala is a Lecturer in the department of Industrial Engineering and Engineering Management in the college of Science, Engineering and Technology at the University of South Africa (UNISA), Florida, South Africa. She holds a Master of Engineering in Management and Information Systems Engineering from Nagaoka University of Technology, Japan, a Master of Business Administration (MBA) from the University of Witwatersrand, South Africa and a Postgraduate Certificate in Education in Senior phase and Further Education and Training Teaching from University of South Africa (UNISA). Her research interests include optimization, sustainability, supply chain and quality management systems. She is a member of SAIIE.

Ngaka Mosia is a Lecturer in the department of Mechanical and Industrial Engineering, in the school of Engineering and a College of Science, Engineering, and Technology at the University of South Africa (Unisa), in Gauteng, South Africa. He holds a BSc (Hons) in Applied Science from the University of Pretoria (UP), a BTech in Industrial Engineering from the University of Johannesburg (UJ), a MPhil in Engineering Management from the University of Johannesburg (UJ), and a post-graduate certificate in Distance Education from the University of Maryland University College (UMUC). He has journals, conference papers, and posters. His research interests include technology-mediated teaching and learning and Productivity improvement through mechanization, and healthcare optimization. He is a member of SAIIE & IEOM and Nadeosa & DEASA.