Sufian, AT, Abdullah, BM and Miller, OJ

Smart Manufacturing Application in Precision Manufacturing

applied sciences

MDPI

Article

Smart Manufacturing Application in Precision Manufacturing

Amr T. Sufian [1,*], Badr M. Abdullah [1] and Oliver J. Miller [2]

[1] School of Civil Engineering and Built Environment, Faculty of Engineering and Technology, Liverpool John Moores University, Liverpool L3 3AF, UK; b.m.abdullah@ljmu.ac.uk
[2] Beverston Engineering Ltd., Prescot L34 9AB, UK; oliver.miller@beverston.co.uk
* Correspondence: a.t.sufian@ljmu.ac.uk

Featured Application: This work bridges the gap between theory and practice by rapidly implementing smart manufacturing application in industry using a systematic roadmap. It shows actual business benefits and impacts to drive and accelerate industry 4.0 adoption in the manufacturing industry, especially for SMEs.

Abstract: Industry 4.0 presents an opportunity to gain a competitive advantage through productivity, flexibility, and speed. It also empowers the manufacturing sector to drive the sustainability revolution to achieve net zero carbon by reducing emissions in operations. In this paper, the aim is to demonstrate a practical implementation of a smart manufacturing application using a systematic approach based on conceptual six-gear smart factory roadmap with connectivity, integration and analytics stages to build a smart production management ecosystem using off-the-shelf technologies applied in precision manufacturing. Business benefits from the smart manufacturing application implementation are realized in terms of operational performance, economic benefits, and environmental sustainability over a period of three years (before and after smart manufacturing). The productivity improves as a result of the 47% improvement made to the machines' utilization and the 53% reduction in the total downtime waste. Economic benefits are realized in terms of a cost saving of GBP 420 K that could cost the business and the returns of the financial investment made, which is recovered within a year. An environmental sustainability impact is realized by a reduction in the total greenhouse gas (GHG) emissions by 43%, mostly due to the reduction in the Scope 2 emissions in operations by 50%, which is significantly impacted by the reduction of energy consumption and better power consumption management. The significance of this work is the bridging of the gap between theory and practice by rapidly applying the six-gear smart factory roadmap to start, scale, and sustain the implementation of smart manufacturing applications in the manufacturing industry. This roadmap can serve as a strategic framework tool for smart manufacturing implementations. The technical architecture can serve as a guide for the practical implementation of smart manufacturing applications to reduce the complexity of development. This work also bridges the gap in academia and in industry by showcasing a real-world actual business benefits realized from smart manufacturing, as well as showcasing the practical implementations, limitations, and opportunities of smart manufacturing applications in the precision manufacturing industry, all of which reduce the internal barriers and challenges facing smart manufacturing and industry 4.0 adoption. The value realized in gaining a competitive advantage and driving environmental sustainability from smart manufacturing in this study can serve as a case study for academics and for industry business leaders, digital champions, and digital lighthouses to support value creation and to drive and accelerate smart manufacturing applications, digital transformation initiatives, and industry 4.0 adoption across the value chain.

Academic Editors: Ugljesa Marjanovic, Slavko Rakic and Nenad Medic

Received: 20 August 2024
Revised: 7 January 2025
Accepted: 9 January 2025
Published: 17 January 2025

Citation: Sufian, A.T.; Abdullah, B.M.; Miller, O.J. Smart Manufacturing Application in Precision Manufacturing. *Appl. Sci.* **2025**, *15*, 915. https://doi.org/10.3390/app15020915

Keywords: smart manufacturing; industry 4.0; digital transformation; operational performance; environmental sustainability

1. Introduction

Innovation and technology have played a significant role in transforming the manufacturing industry. The development of irrigation engineering techniques over the years has transformed agricultural society. The progress in mathematics and in mechanics in the 9th and 12th centuries, respectively, led to the first automation of machines that translated rotary motion into linear motion. This subsequently enabled the development of self-driven water-rising machines, water pumps, and later stream power in the late 18th century, which enabled the industrial transformation [1]. The increase in mechanization, the spread of electricity, and the introduction of the assembly line concept the late 19th century enabled mass production. The advancements in electronic devices and IT systems, which made robotics and automation possible in the second half of the 20th century, enabled mass customization. The advancements in the internet, computing, communication technologies and data science in the 21st century have disrupted industry with the fourth wave of industrial revolution, enabling mass personalization [2].

Digital transformation refers to the process of using digital technology to improve or create new business processes, culture, and customer experience to meet changing business and market requirements. Smart manufacturing is a term used to define the application of digital technologies and industry 4.0 concepts in the factory in order to enhance manufacturing processes. It involves the integration of various technologies, data analytics, and human ingenuity to improve manufacturing, production, speed, quality, and overall efficiency, which, as a result, reduce waste and contribute to customer value. On the other hand, the lean philosophy is about removing waste from a process using a set of methodologies summarized as value, value stream, flow, pull, and perfection. These methodologies require data to be collected, information to be analyzed, insights to be realized, and improvements to be made, which eventually lead to less waste and improved effectiveness. Smart manufacturing provides visibility into the manufacturing processes and allows relevant information to be distributed to every level of the enterprise, turning data into actionable insights. This provides support to lean methodologies to quickly identify and map the value stream as well as measure and analyze insights for improvements to be made and waste to be removed from the process. For example, the application of IoT provides data and insights to empower value stream mapping for the steps that do not create value to be identified and eliminated. The application of AI in manufacturing provides further insights for perfection. The automation of data flow across systems enables flow and pull methodologies, for example, by providing an alert if a defect or a problem is encountered, enabling root cause analysis to be performed and preventing defects from being passed upstream. The relationship between smart manufacturing and the lean methodology is that they share common expected outcomes, which are waste reduction and cost competitiveness; therefore, lean manufacturing implementation integrated with smart manufacturing leads to high operational performance improvements [3]. Smart manufacturing supports continuous improvements and lean principles, making lean and smart manufacturing complement each other [4].

The term industry 4.0 was coined in Germany over a decade ago to indicate the birth of a new era of manufacturing, offering opportunities to improve productivity and competitiveness [5]. Today, there are more complex challenges facing industry, mainly associated with resilience, sustainability, and skills. Recent industrial reports stress that some of the critical challenges facing the manufacturing industry are related to supply chain constraints, inflation, economic pressure and uncertainty, cybersecurity risks, shortage of skills and talent acquisition, rising energy costs, climate change, and dramatic changes in geopolitics [6–9]. The recent pandemic has already highlighted the importance of a robust, transparent, and more resilient supply chain [10–12]. The emerging environmental, social, and governance (ESG) sustainability goals to mitigate the internal risks are major considerations for driving digital transformation and industry 4.0 adoption [6,13]. Further calls are now driving an evolution of industry 4.0 to be more intelligent, green, and human-centric, aligning it with the vision of industry 5.0 [14,15].

To address the global challenges facing the manufacturing industry, governments have been setting strategies to develop and implement advanced manufacturing technologies to build resilience and sustainability into manufacturing and its supply chains. Industrial reports have continually recommended digital transformation and the adoption of industry 4.0 across the manufacturing value chain to protect long-term profitability by improving resilience and agility, driving productivity, and focusing on corporate social responsibility. Manufacturers that have accelerated their digital transformation and the adoption of industry 4.0 have shown greater resilience and agility to supply chain challenges by having increased visibility and being able to pivot faster [12]. Smart manufacturing implementations have also been progressing in laying the technology foundations and connectivity as companies tend to expand their capabilities and build new ones [16].

But, despite the rapid increase in the literature on industry 4.0, its general adoption is still immature and has been progressing slowly [17]. Industrial studies suggest that only one-third of digital transformation initiatives are considered successful and have met their organizational objectives [13]. As a result, the impact on global productivity and economic growth has been less pronounced than anticipated. Several factors that have contributed to this slower-than-expected progress are external due to the industry challenges mentioned earlier and others are internally based. Amongst the top internal barriers reported by industry and in the academic literature are budget resources constraints [6,7], the high cost of technology investment and digital transformation [6,7,18], the lack of technical skills to implement/optimize smart manufacturing adoption [6,7,18,19], the complexity of the deployment and integration of new technologies associated with industry 4.0 [6,18], and the lack of clear and well-defined strategies and clarity of economic business benefits that drives value [7,13,17,20–23]. Small and medium enterprises (SMEs), in particular, share common struggles regarding the high cost of implementation, unclear return on investments, and the lack of digital skills to benefit from industry 4.0 [24]. To address such barriers, study findings from industry and the academic literature have recommended practical and comprehensive strategic frameworks to support manufacturing companies with its implementation, showcasing the impact on business objectives, performance, and economic indicators [7,13,17,20,25]. This work seeks to address this gap.

Recent empirical analytical studies have investigated the impact of smart manufacturing on operational performance, financial performance, and sustainability; such investigations showed a positive contribution leading to a competitive advantage. For example, Arcidiacono and Schupp [26] investigated the impact of smart manufacturing applications across 234 organizations across Europe, covering original equipment manufacturers (OEMs) as well as Tier 1 and Tier 2 suppliers from the automotive industry, on operational performance benefits (such as quality, cost, productivity, delivery, and flexibility) and financial performance elements related to profit margins. The findings highlighted that the adoption of smart manufacturing results in improvements in operational performance and supports a firm's financial performance in maintaining competitiveness. Another study by Saleem, et al. [27] investigated the impact of the smart factory adoption of 240 organizations in

Korea, which covered a wide range of firm sizes from multiple important Korean industrial segments including automobile, electronics, semiconductors, electrical, communication, chemicals, metals, and machinery on manufacturing performance elements related to productivity and sustainable manufacturing (such as waste reduction, energy consumption). The findings showed a significant and positive contribution that led to productivity improvements and sustainability enhancements. Such empirical studies have confirmed the scarcity of research measuring the actual performance of manufacturing firms that have already adopted smart manufacturing applications, and this work seeks to address such gap.

Another study by Maretto, et al. [25] investigated the real-life adoption of digital technologies within industrial plants and how such implementations have affected both performance and economic viability. The study was based on 299 case studies produced in the academic literature between 2015 and 2022. The findings highlight that out of all the investigated case studies, 41% provided a form of performance evaluation, and only 13% included a form of economic assessment. The study also indicated that the academic literature focused more on the technical implementation aspect of digital technologies but lacked an evaluation of the application with specific key performance indicators (KPIs) and economic indices. This finding was also pointed out in a previous study by Ivanov, et al. [20], who examined the state-of-the-art research in industry 4.0 based on an analytical literature review and a global survey of 238 studies from different industry 4.0-related disciplines. The findings indicated a scarcity of academic works that dealt with operational and real-life aspects, such as performance measurements and cost–benefit analysis. The lack of clarity of the real economic benefits of the implementations of digital technologies within industrial plants requires urgent academic attention, which can be addressed through case studies. These findings confirm the research gap in terms of the performance and economic benefit analyses of smart manufacturing implementation case studies in industry, and this work seeks to address this gap.

Another interesting finding by Matetto, et al. [25] highlighted that the most frequent digital technologies applied in industrial plants were related to smart manufacturing applications and that such applications involved the use of multiple groups of digital technologies integrated together, with those at the plant level having the most impact. However, the lack of strategic vision and the lack of understanding of the nature industry 4.0. were two of the most significant limitations that inhibited its adoption [20]; therefore, there is a need for a simplified, less complex framework to assist manufacturing companies with an implementation strategy for the technology integration of smart manufacturing applications in a plant. This work seeks to address this gap.

According to reports that gauged the readiness of the manufacturing industry for smart transformation, the industries in the bottom five were all dominated by SMEs, and the precision manufacturing industry scored the lowest on the maturity scale [21]. This work sought to address this issue by focusing on its application in a precision manufacturing SME as a case study to catalyze the transformation in this space. Precision manufacturing is a cutting-edge technique that produces precise products by leveraging advanced technology, skilled workers, and specialized machinery to achieve accurate and consistent-quality processes. It differs from general manufacturing methods because it places accuracy and quality above mass production. Machining processes such as milling, turning, drilling, grinding, and laser cutting are examples of precision manufacturing. It involves using cutting-edge equipment (e.g., lathes, mills, grinders, and drills) and cutting-edge tools to accurately shape a part or component to the desired specification. Computer numerical control (CNC) machines are computer-controlled and can be programmed to perform specific operations with extremely tight tolerances and high accuracy that result in exceptional precision, making them ideal for precision manufacturing. Applications of precision manufacturing can be found mainly in the aerospace and defense, medical device, and electronics industries because of the demand for high-performance, reliable components, as well as top-quality, safe, and effective products. Hence, the implementation of smart manufacturing applications within precision manufacturing is important for industry to further improve its efficiency, productivity, and quality.

Previous work on different strategies and methodologies for smart manufacturing implementation have been reviewed, and a conceptual approach based on a six-gear roadmap was proposed as a rapid tool for implementing smart manufacturing applications [28]. Case studies have been published that show how such a simple yet practical approach was successfully applied in industry during a collaborative knowledge transfer project between Liverpool John Moores University and Beverton Engineering [29,30].

This work aimed to demonstrate a real-world practical implementation of a smart manufacturing application in a precision manufacturing SME using a systematic roadmap for adoption while showcasing the business benefits in relation to operational performance, economics, and environmental sustainability impact over a three-year period (before and after smart manufacturing implementation). The application of the conceptual six-gear smart factory roadmap for implementing a smart manufacturing application is demonstrated using technical architecture diagrams and design building blocks to serve as a technical guide for the implementation of smart manufacturing applications in practice using available off-the-shelf technology solutions.

This work also serves as a real-world case study that demonstrates actual business benefits and can help manufacturers reduce the barriers to smart manufacturing implementation and accelerate digital transformation and industry 4.0 adoption. It also aims to bridge the gap between theory and practice in terms of actual business benefits, practical implementations, challenges, limitations, and potential opportunities.

Section 2 describes the methodology adopted for implementing the six-gear smart factory roadmap, focusing on the technical stage's connectivity, integration, and analytics. The old landscape (before smart manufacturing implementation) is outlined together with the new landscape (after smart manufacturing implementation) for each stage in relation to the manufacturing systems used as well as how they are connected, integrated together, supported by their technical design implementation architecture. Section 3 presents the results related to machines' utilization, productivity improvements, cost savings, and emission reductions for the period of three years after smart manufacturing implementation. Section 4 discusses the results and the impact on the manufacturing SME in terms of operational performance, economic benefits, and environmental sustainability. Section 5 draws conclusions. Finally, potential future work and opportunities are discussed for optimization and scaling the stages of the six-gear smart factory roadmap.

2. Methodology

Figure 1 shows the six-gear smart factory roadmap. It is a conceptual tool designed for the rapid implementation of smart manufacturing applications in the manufacturing industry that is based on a previous publication from 2021 [28]. The concept and methodology of the tool are practically demonstrated in this paper through the implementation of a smart manufacturing application. The methodology adopted is based on the roadmap systematic stages, strategy, connectivity, integration, and analytics. The strategy stage focuses on pivoting the business needs and objectives that can be achieved for a smart manufacturing application implementation. The connectivity stage focuses on asset connectivity on the factory floor through secure and resilient network to achieve the real-time visibility of the production process. The integration stage focuses on the vertical integration of information technology (IT) and operation technology (OT) across the manufacturing systems to allow production data to be exchanged across multiple functions at the factory and at the enterprise level in relative real time. The analytics stage focuses on building an enterprise intelligence by digitizing the collected data and reporting capabilities. The artificial intelligence (AI) and the scale stages were not covered as part of this smart manufacturing application implementation but were briefly discussed as part of future potential opportunities for development and optimization of the roadmap at the end of the study to scale such implementation.

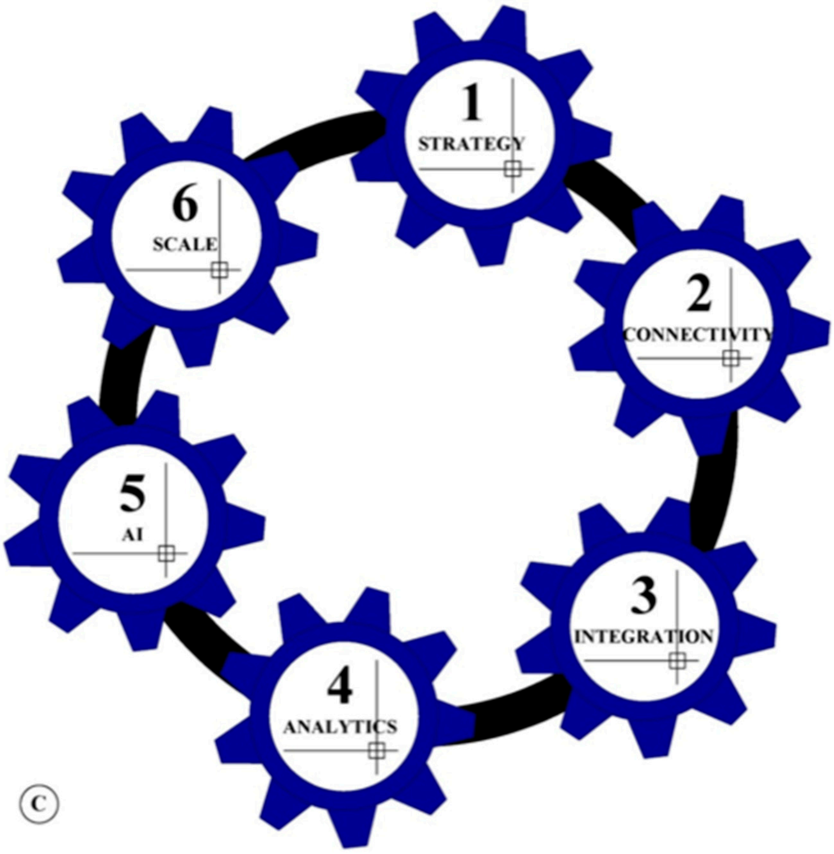


Figure 1. The six-gear smart factory roadmap (source: Sufian, et al. [28]).

Figure 2 shows a diagram of the international standard ANSI/ISA-95 traditional manufacturing system integration layout that has been widely applied in manufacturing. It provides the terminology for the applications and their functionality to show how systems are integrated together and how information is exchanged between the different layers [31]. It also represents the hierarchy levels of the Reference Architecture Model for Industrie 4.0 (RAMI 4.0), which shows the different functionalities within factories/plants, which are also part of the international standard series for enterprise IT and control systems: IEC62264 [32]. The ISA-95 framework is used to show the pre-smart manufacturing application implementation state and post-smart manufacturing application implementation state for the connectivity, integration, and analytics stages to demonstrate a step-by-step systematic approach of how such manufacturing systems can be connected and integrated to build smart manufacturing applications. The connectivity, integration, and analytics stages are also supported by a technical architecture diagram to demonstrate the technical aspects of the implementation. The ISA-95 diagram in Figure 2 consists of five traditional operational levels (0–4), where the manufacturing applications and systems contain relevant manufacturing operation information. The sixth layer (Level 5) is added to the diagram to represent the analytic and insight layers, which are represented by data analytic tools and applications (e.g., business intelligence systems) and advanced analytics applications (e.g., machine learning) to report the performance and provide insights into the manufacturing operations process.

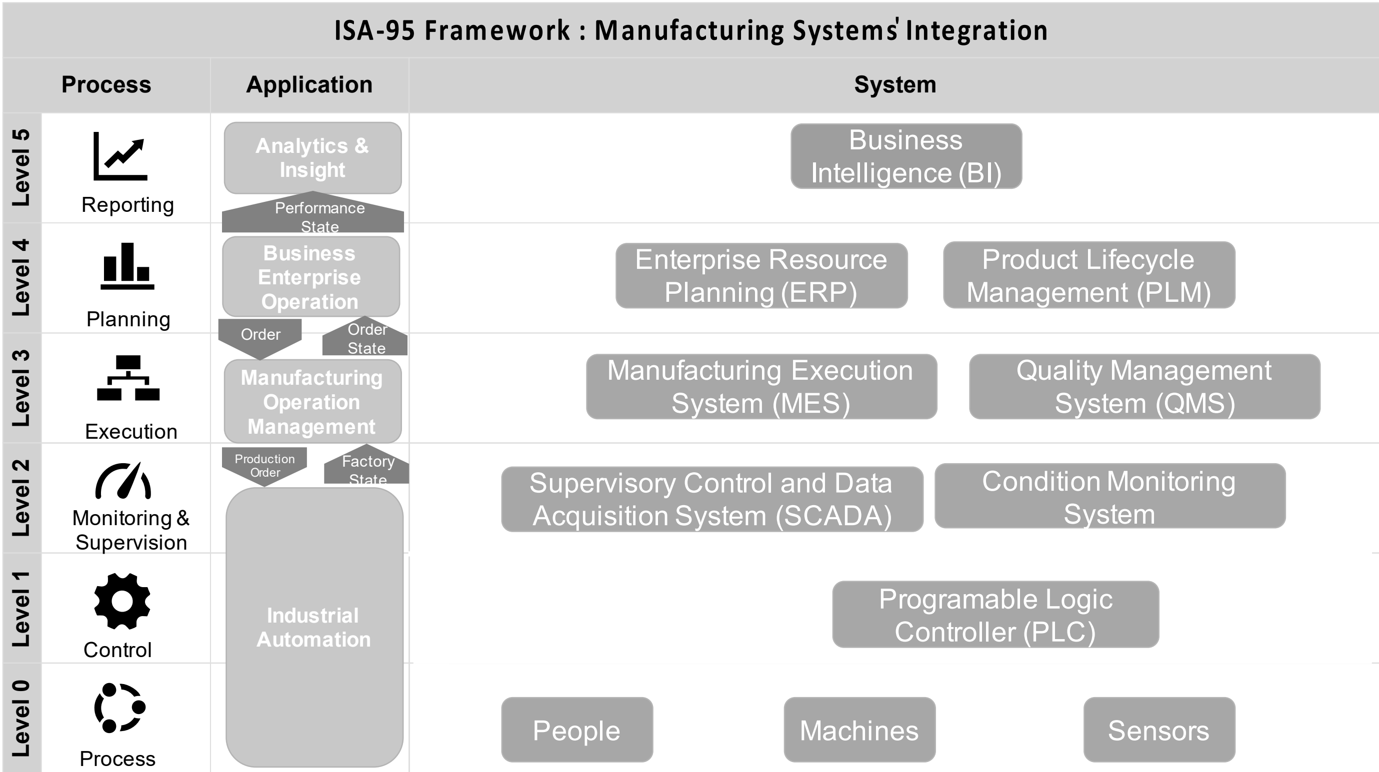


Figure 2. Traditional ISA-95 framework diagram of manufacturing systems' integration (authors' creation).

2.1. Strategy Stage

The business realized that to stay competitive in the precision manufacturing industry, it needed to improve productivity and reduce waste. However, the digital and smart industry readiness was immature. In particular, there was no connectivity to the production machines on the factory floor; therefore, the performance or the production process was not visible. Additionally, there was no digital system in place to manage production orders, so the processes were carried out manual and fully dependent upon the individual skills of the production management team. This made measuring production using KPIs difficult as they were calculated from manual data, which were subject to human error and out of date because they were assessed after the event. This made the factory and workforce performance less efficient. As a result, more downtime waste (i.e., lost production time) was produced, which impacted the cost of production as well as limited the production capacity, agility, resilience, and growth.

To achieve the business objectives, it was required to build a smart production management ecosystem. Improvements to the IT infrastructure and secure connectivity of the production machines were initially required to have full visibility of what was happening on the factory floor. The exchange of relevant production information required automation so information could be shared with the enterprise IT system in the office for the real-time management of the production process and for daily repetitive tasks to be eliminated. Business KPIs were also required to be digitally reported in real time to rapidly manage deviation and adapt to changing needs. The strategy was to adopt industry

4.0 concepts and technologies to transform into smart manufacturing using off-the-shelf available technologies for rapid implementation.

Improvements to productivity and reductions in downtime waste can be achieved by automating the repetitive daily tasks and by having access to real-time production information to provide actionable insights to quickly determine operational bottlenecks. Improvements to KPI reporting can be achieved by improving their collection method and the speed they are reported to the relevant stakeholders so actions can be taken rapidly.

Improvements to manufacturing capabilities can be achieved by better monitoring the asset's health as well as the performance and use of the production machines in the factory so that unscheduled downtime can be reduced, and production time management can be improved. As a result, a market advantage can be achieved for a smart production line and speed to market can be increased by bringing improvements quickly to production planning and job scheduling.

Figure 3a shows the ISA-95 manufacturing system integration architecture of the base state of the factory (before smart manufacturing implementation). Figure 3b shows the connectivity and integration architecture between the factory floor and office. In the factory layer, fifteen CNC manufacturing Mazak machines were networked via ethernet cables to the network mainly for the purpose of storing and transferring CNC programs across the network. The grinder machine (Machine 16) was not connected to the network because of the complexity involved due to it being a legacy machine with the only Fanuc controller in the factory, which required a separate computer interface for communication and a configuration setup, neither of which were available at the time. The manufacturing IT system in the network was an enterprise resource planning (ERP) system. The ERP system in the network was directly connected to multiple PCs on the factory floor that are used as a human–machine interface (HMI) for production reporting by the operators of the machines.

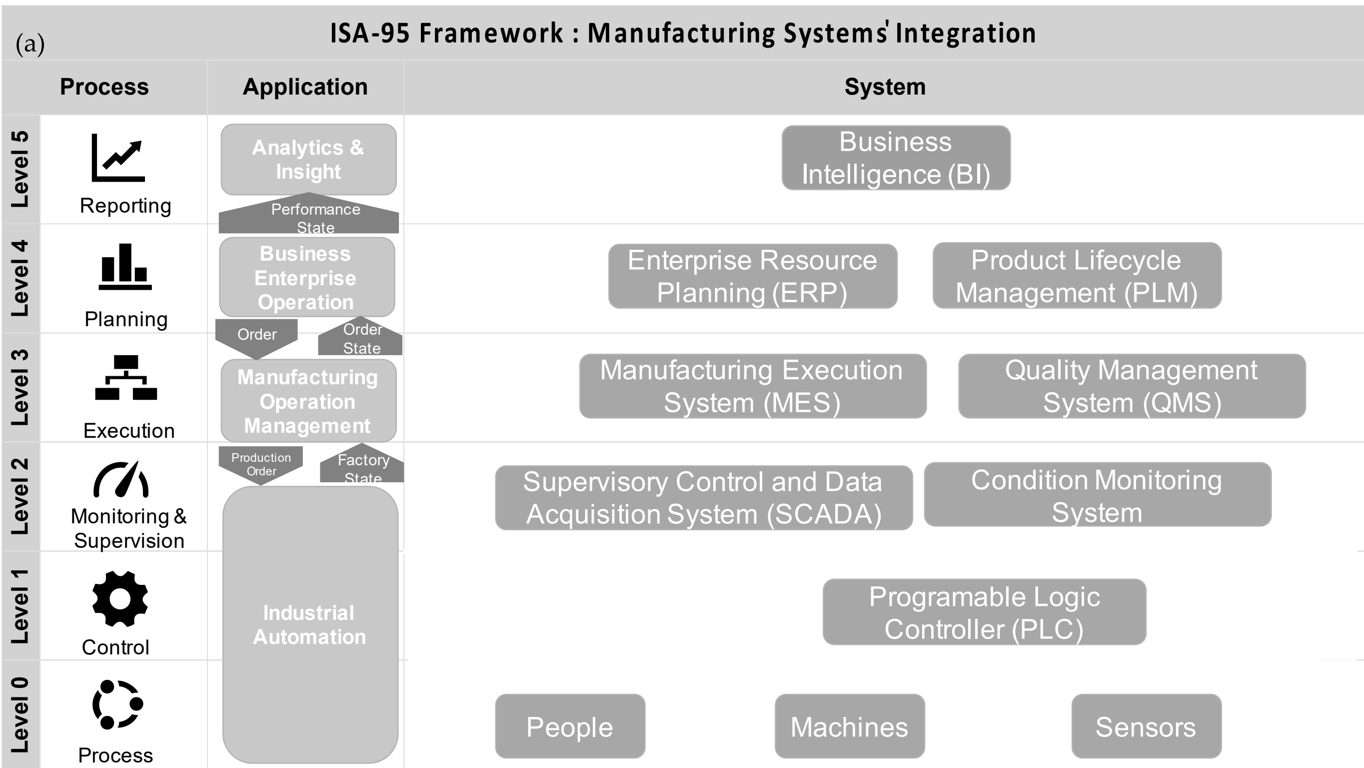


Figure 3. *Cont.*

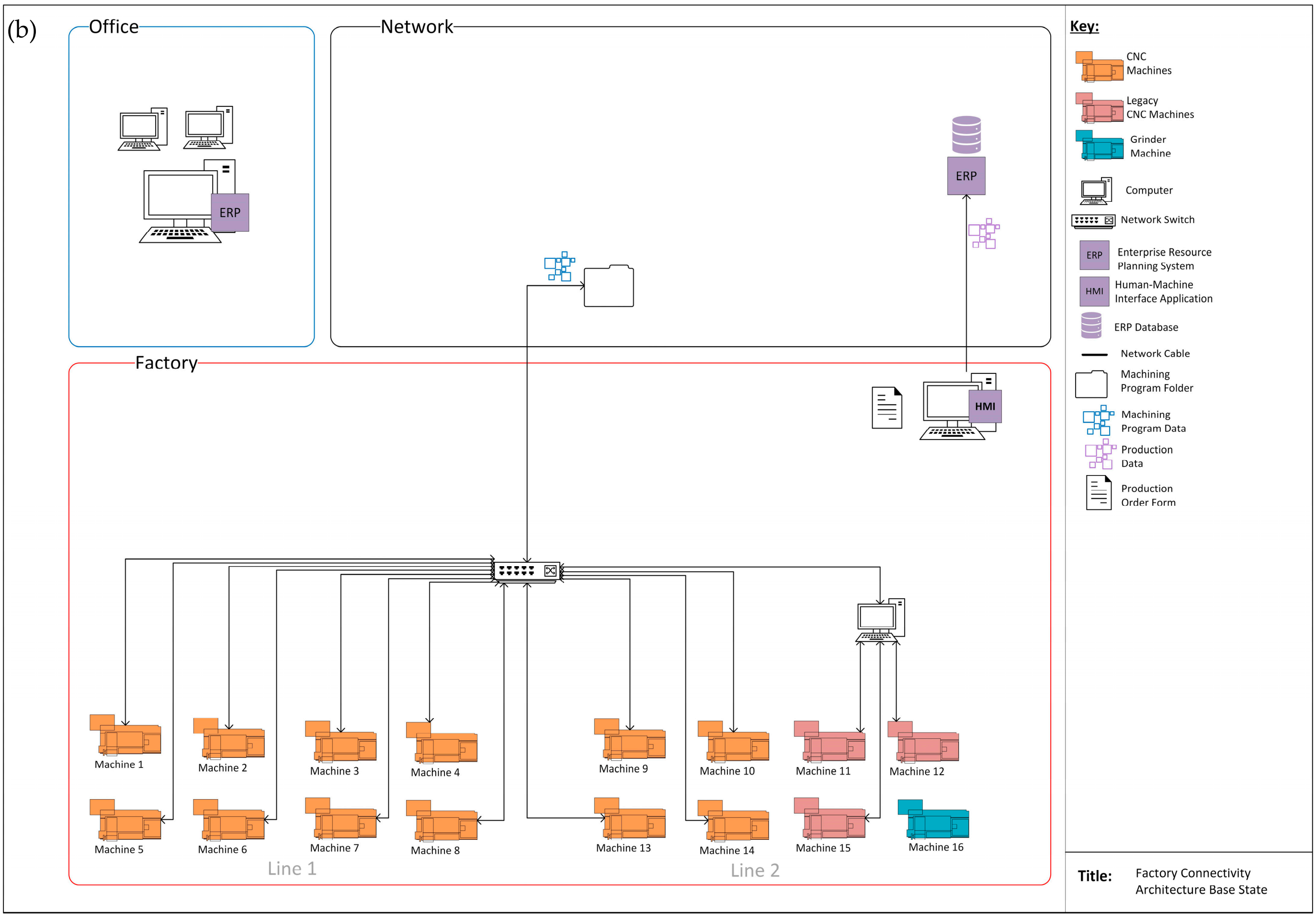


Figure 3. Base state of integrated manufacturing system architecture: (**a**) ISA-95 diagram; (**b**) manufacturing system connectivity and integration architecture.

2.2. Connectivity Stage

Connectivity is the backbone of industry 4.0. It is related to the interconnectedness of the OT that resides within the factory floor (e.g., machines) and the IT that resides in the enterprise (e.g., computer-based systems). The concept of connectivity under industry 4.0 means more devices and systems that once were independent and/or isolated are being connected via digital means to generate enormous amounts of manufacturing data that can be easily accessed. However, formal connections need to be established across assets and systems to ensure the interoperability, security, speed, and agility of the network. These qualities allow interconnected systems to communicate with one another seamlessly and allow them to be reconfigured dynamically in response to changing needs [22].

In this stage, the scope was to connect the CNC machines. The starting point was to enhance the network infrastructure in the factory with stable, resilient, and secure capabilities for seamless connectivity. A dedicated factory network server was installed and segregated from the enterprise network using two Cisco Industrial Ethernet (IE) 4000 switches provided by Mazak's SMARTBOX™ (Mazak Corporation, Takeda, Japan) technology [33,34], embedded with a high level of network security protocols to prevent any issues with unauthorized access from and to the machines on the network, safeguarding the manufacturing process. They were mounted to the sidewall of the factory and connected to the machines via network ethernet cables; direct connection to the machine's electrical cabinet was not needed.

The connectivity to the CNC machines was established using an ecosystem of technology elements that collected, stored, and visualized the data of the machine's condition and the machining process. The technology stack provided by Mazak's iSMART Factory™ solution [33] represented a cost-effective yet secure by-design digital connectivity solution for the CNC machines. MTConnect communication protocols were used as the standard methods for communication and data representation, which have been widely used in industrial environments [35]. The technology layers of the iSMART Factory ecosystem solution consisted of an IIoT gateway communication layer and an application management layer. The IIoT gateway consisted of four sublayers: Thing, Sensor, Edge, and Communication. The Thing was the actual CNC machine with its actuators (e.g., 3–5 axes spindle). The Sensor was the sensor embedded within the CNC machine itself manufactured by the OEM, and the Edge was the PLC unit that operated and controlled the CNC machine. The Communication layers consisted of software adapters, ethernet network cables, and software agents. The software adapter (MTConnect-based) used an industrial standard communication protocol for data extraction that was installed on the CNC machine control computer operator that controlled the PLC. The Ethernet network was the communication method of transporting data through the network from the CNC machine through the industrial switch to the server. The software agent (MTConnect-based) was installed inside the industrial switch (Mazak Smart Box) that had computing capability, allowing the software agent to interpret the relevant manufacturing data from multiple machines connected to the industrial switch before they were passed to the client application management at the server. This industrial network switch also acted as north/south bound network cybersecurity divider layer with secure network connectivity features, allowing device verification and the one-direction flow of data from the factory floor network to the office network, safeguarding CNC machines connected and preventing vulnerable hacks that can leak information, damage equipment, or even cause personal injury. The application management layer consisted of a Smooth Monitor AX and a database. The first was a client management application installed in the office network that was used to manage the machines' connectivity and for visualization. The latter was a Microsoft SQL database used to store data for later integration with other IT systems.

Figure 4a shows the ISA-95 diagram for the connectivity stage where the CNC machines in Level 1 are connected to the condition monitoring system in Level 2. Figure 4b shows a connectivity architecture diagram, with the iSMART Factory solution IIoT gateway layer in the southbound factory network and the application management layer in the northbound factory network.

2.3. Integration Stage

Integration is a key characteristic of industry 4.0. It focuses on the vertical integration of processes within operations as well as horizontal integration across the supply chain and product life cycle integration to manage the entire lifecycle of a product. This is achieved by an ecosystem of interconnected systems that allows data to be exchanged, with processes integrated across the value chain, which result in improved communications and an improved manufacturing process, with leaps forward in agility, efficiency, and customer satisfaction.

Vertical integration is associated with the integration of the operational processes that lead to the production of goods and services [22]. Manufacturing processes that encompass production planning and scheduling as well as production execution/control are included within this scope. This was aligned with the strategy of creating a smart production management system for smart manufacturing.

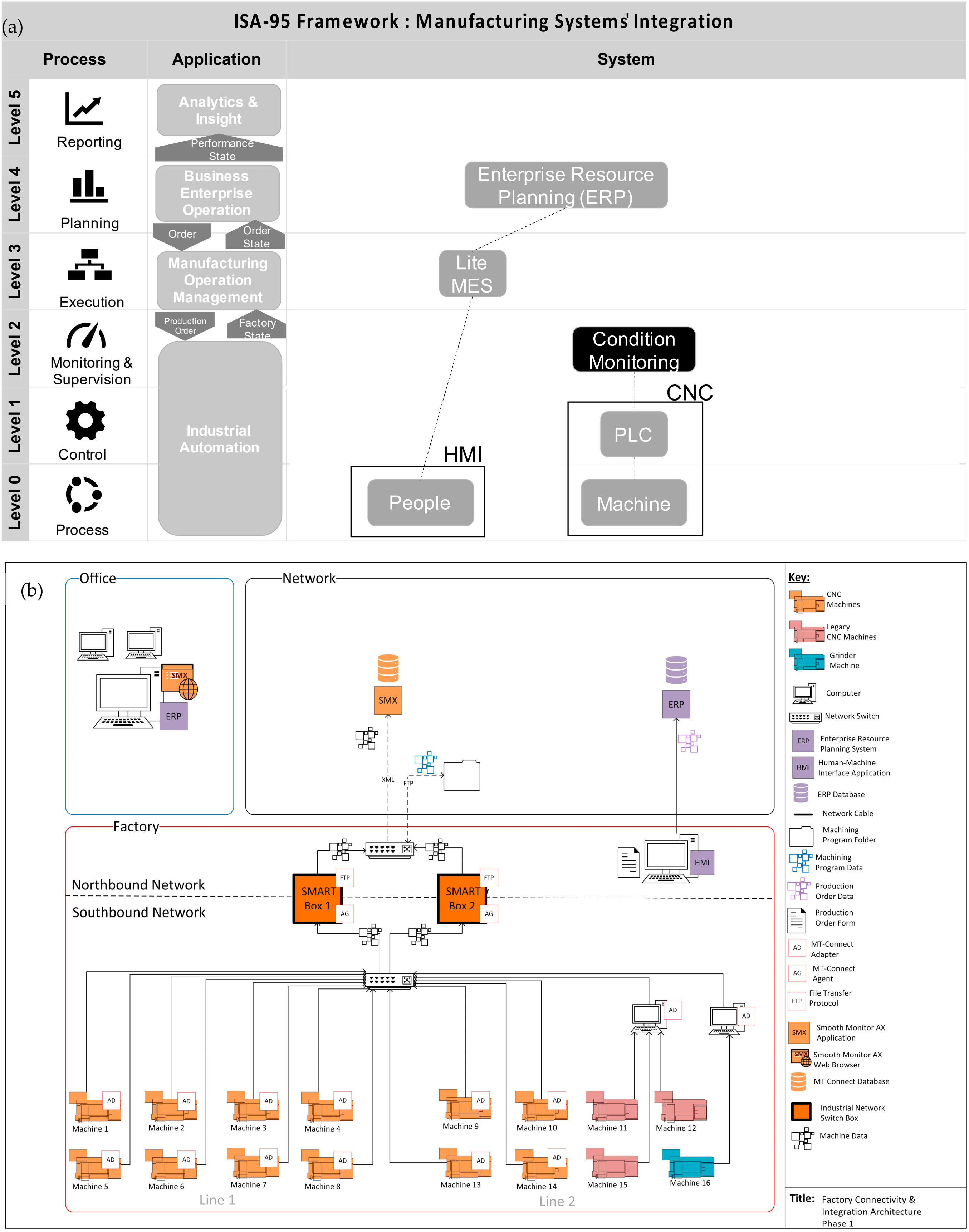


Figure 4. Architecture of connectivity stage of manufacturing system integration: (**a**) ISA-95 diagram; (**b**) manufacturing system connectivity and integration architecture.

In this stage, vertical integration is achieved by integrating the business's enterprise IT system (e.g., ERP) with the manufacturing operations' management OT system (e.g., MOM) as well as the monitoring and supervision OT system (e.g., condition monitoring system) at the factory floor across the hierarchical of the ISA-95 level pyramid. Manufacturing data are exchanged via digital means and in relatively real time. As a result, it automates the relevant manufacturing processes (e.g., production orders release) and the exchange of relevant production and quality information (e.g., work in progress, production, and quality attributes) to different stakeholders across operations to gain insights into the manufacturing process, allowing fast and proactive decision making that enables the concept of data-driven intelligence in manufacturing operations.

Figure 5a shows the ISA-95 diagram for the integration stage, where the production management system in Level 3 is vertically integrated upstream with the ERP system in Level 4 and downstream with the condition monitoring system in Level 2 and people and sensors in Level 0.

Figure 5b shows the integration architecture diagram where the Supervised Manufacturing Acquisition System (SMAS) by Datahone functions as a production management system. SMAS was integrated with Epicor ERP through REST communication protocols for exchanging bi-directional production information such as work order and schedule status. SMAS was also integrated with the Smooth Monitor MT-Connect database through SQL queries for near-real-time updates on machine status. Machine operators could access the SMAS web-interfaced machine dashboards via HMI tablets that were stationed next to each CNC machine, providing them with near-real-time updates on current production and quality information. Environmental sensors on the factory floor were integrated with the SMAS through an IIoT gateway using Brainboxes ED-549 (Brainboxes Ltd., Liverpool, UK) [36] that had multiple wired sensors connected. These sensors measured the current at the mains coming from the factory substation, the vibration of the air compressors, and the temperature of the factory at multiple locations. The IIoT gateway took analogue signals and turned them into digital data to be transferred to the network through a low-bandwidth Message Queuing Telemetry Transport (MQTT) communication protocol, to be visualized using the SMAS plant view dashboard.

2.4. Analytics Stage

Analytics represents the intelligence pillar that acts as the brain that powers industry 4.0. The analytics stage is about processing and analyzing data that have been collected from different IT/OT systems within manufacturing to gain insights to identify and diagnose any deviations and adapt to the changing needs of the organization.

Smart manufacturing is about data-driven intelligence, where the vast quantities of data generated from different manufacturing systems can be processed and translated into actionable insights to diagnose problems and identify opportunities for improvements. In this stage, data are collected, structured, condensed, and analyzed in relative real time using a business intelligence (BI) system such as Microsoft Power BI, turning data into actionable information via light and accessible digital dashboards with reports that display the relevant KPIs and insights related to production, quality performance, financial elements, etc.

Figure 6a shows the ISA-95 diagram for the analytics stage where the IT and OT systems, across the different levels of the framework are integrated with the BI system in Level 5, which reports information relevant for decision making. Figure 6b shows the architecture diagram, where Power BI was used as a cloud-based BI tool that collected data from the ERP, SMAS, and Smooth Monitor AX, and other relevant data in the enterprise through multiple communication protocols including a direct database SQL connection and REST API's, which were the main communication protocols during this stage.

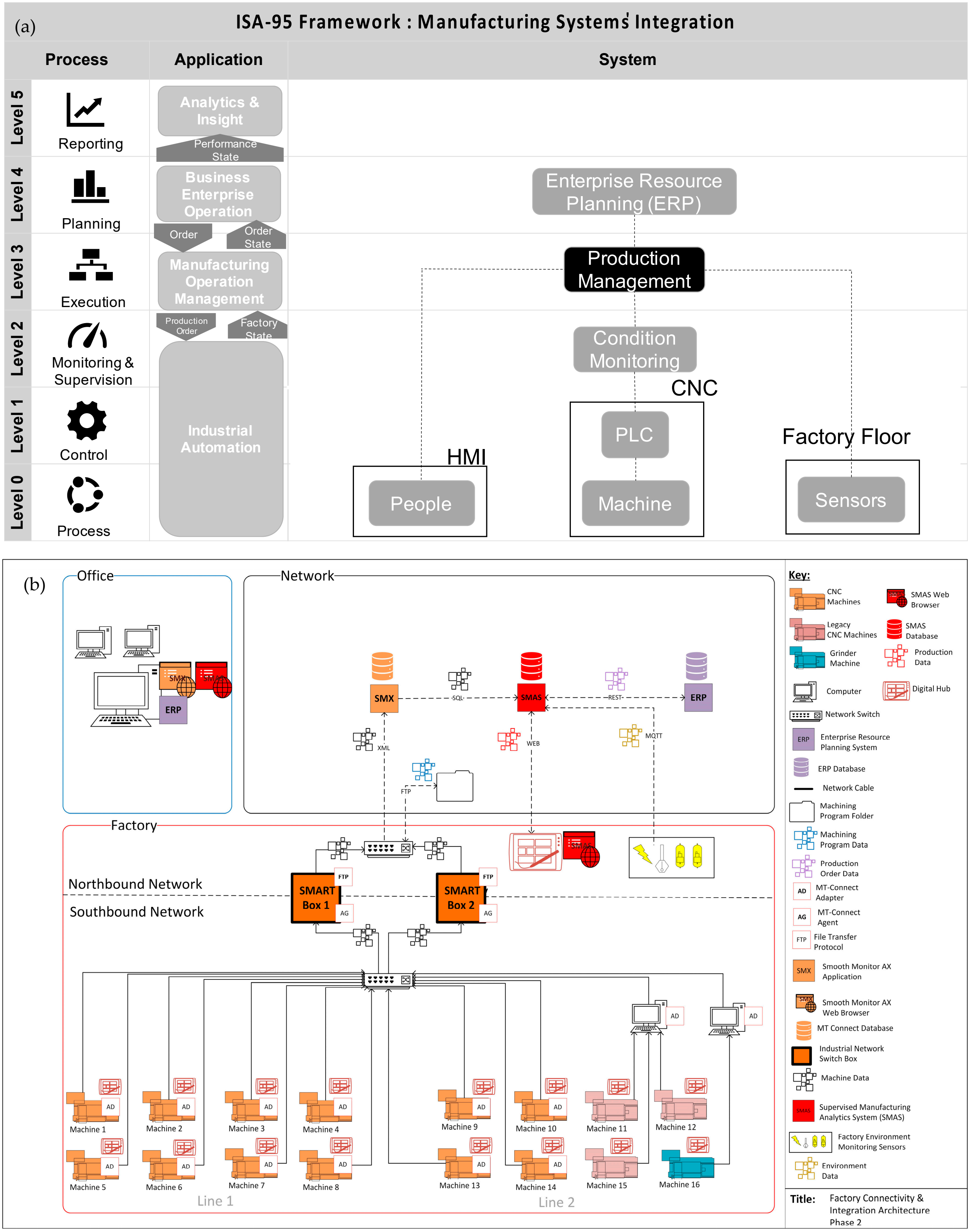


Figure 5. Integration stage of manufacturing system integration architecture: (**a**) ISA-95 diagram; (**b**) manufacturing system connectivity and integration architecture.

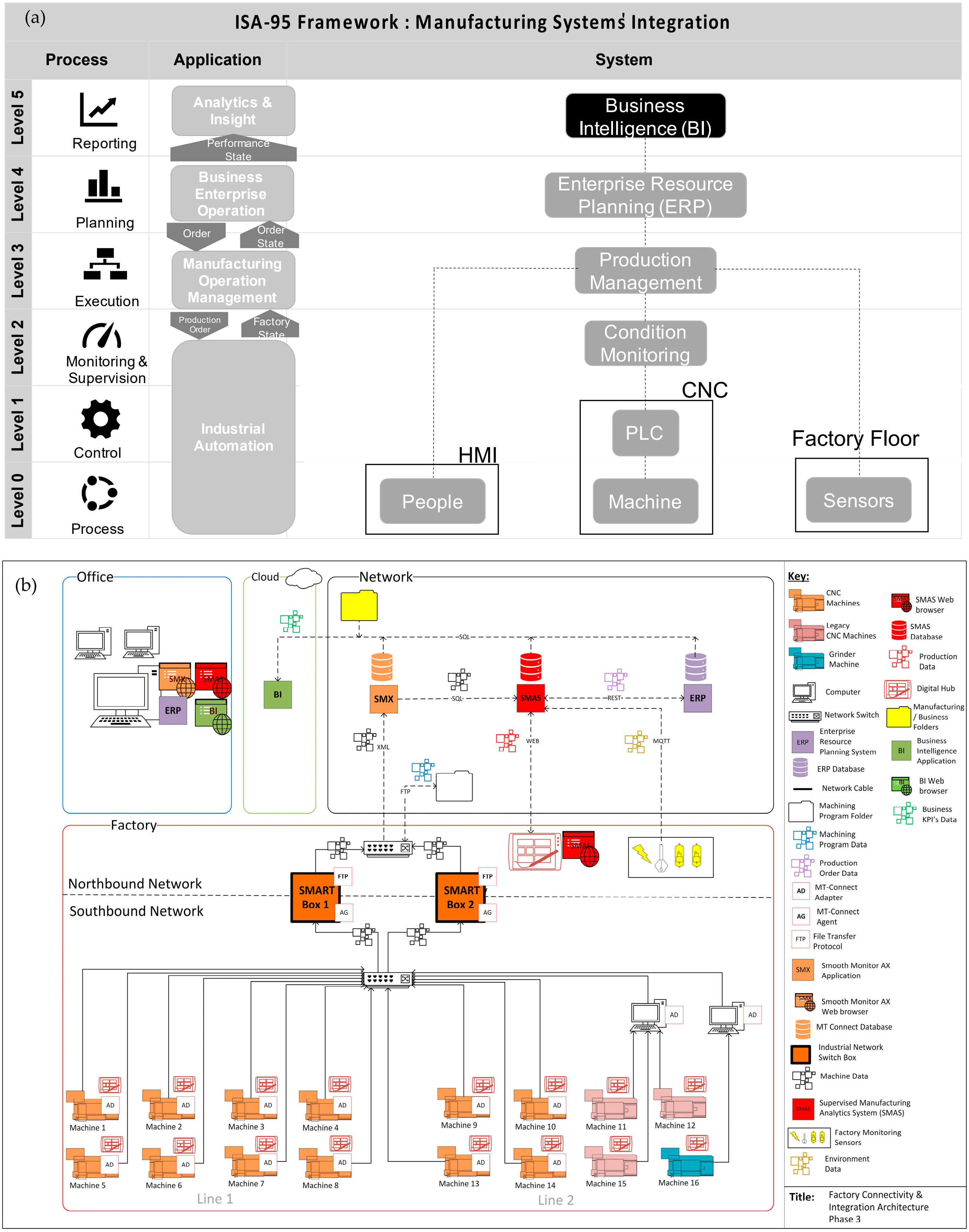


Figure 6. Analytics stage of manufacturing system integration architecture: (**a**) ISA-95 diagram; (**b**) Manufacturing system connectivity and integration architecture diagram.

3. Results

In this section, the results are presented and discussed in three stages. Firstly, an example of the results produced from the smart manufacturing application being implemented in the connectivity, integration, and analytics stages is presented to show the kind of information that was produced relatively in real time for the operators and the management team during daily operations to effectively manage production. Secondly, the productivity performance related to a machine utilization in the factory over a period of three years (2020–2022) is presented and discussed to show the machine utilization performance over time during and after the smart manufacturing application implementation. Lastly, the overall productivity, financial performance, and environmental sustainability performance of the factory over a period of six years (2019–2024) is presented and discussed to show the performance effects over time during and after the smart manufacturing application implementation.

Figure 7 shows example of the data produced in the form of digital dashboards taken at a snapshot in time from the systems that were implemented in the connectivity, integration, and analytics stages of the roadmap.

Figure 7. Examples of the digital dashboards produced in the connectivity, integration, and analytics stages. (**a**) Integrex production line CNC machine condition monitoring dashboard; (**b**) Mill-Turn production line CNC machine condition monitoring dashboard; (**c**) live factory production status production management dashboard; (**d**) machine operator view production management dashboard; (**e**) plant environment view production management dashboard; (**f**) KPI report BI system dashboard.

Figure 7a,b show the Smooth Monitor AX condition monitoring system dashboards implemented in the connectivity stage. These dashboards show the relative real-time condition data of the machines and the machining status of two production lines with a total of sixteen CNC machines connected. These dashboards are web-based applications used as productivity digital displays across the factory floor to encourage better machine operation management and at the office for production monitoring and better maintenance management.

Figure 7c–e show the SMAS production management system dashboards implemented in the integration stage. These dashboards show relative real-time production data integrated with an IT system (the ERP), an OT system (Smooth Monitor Ax), and the factory environment data. Figure 7c shows the factory production status dashboard with near-real-time KPIs such as schedule attainment, OEE, and other factory status information such as relevant alerts related to quality, maintenance, and production as well as the machines events and their statuses. Such information is used to by the production management team to effectively manage production on the floor, manage the production schedule, and the production order attainment. Figure 7d shows the machine operator view dashboard that allows machine operators to receive and communicate production data related to productivity and quality, functioning as a manufacturing execution system (MES). Figure 7e shows the plant environment view dashboard, which displays processed data related to the factory floor environment such as the changes in temperature at different locations in the factory, the total power consumption of the factory, and the compressors' condition status. These dashboards are from a web-based application used as a smart production management tool to improve the productivity, efficiency, resilience, and agility of the manufacturing process.

Figure 7f shows the business intelligence reporting system dashboard implemented in the analytics stage. Such dashboard reports can be accessed remotely via a web application and are used to report KPIs related to the production and quality performance of the factory.

Figure 8 shows the productivity data related to the CNC machines in the factory and their utilization over a period of three years (February 2020–December 2022). Figure 8a shows a bar graph of the machines' condition mode rate (Equation (1)), which is the ratio of the different machine conditions' mode time against the machines' availability time per month (Equation (2)) for a total of sixteen CNC machines for a period of three years (February 2020 to December 2022).

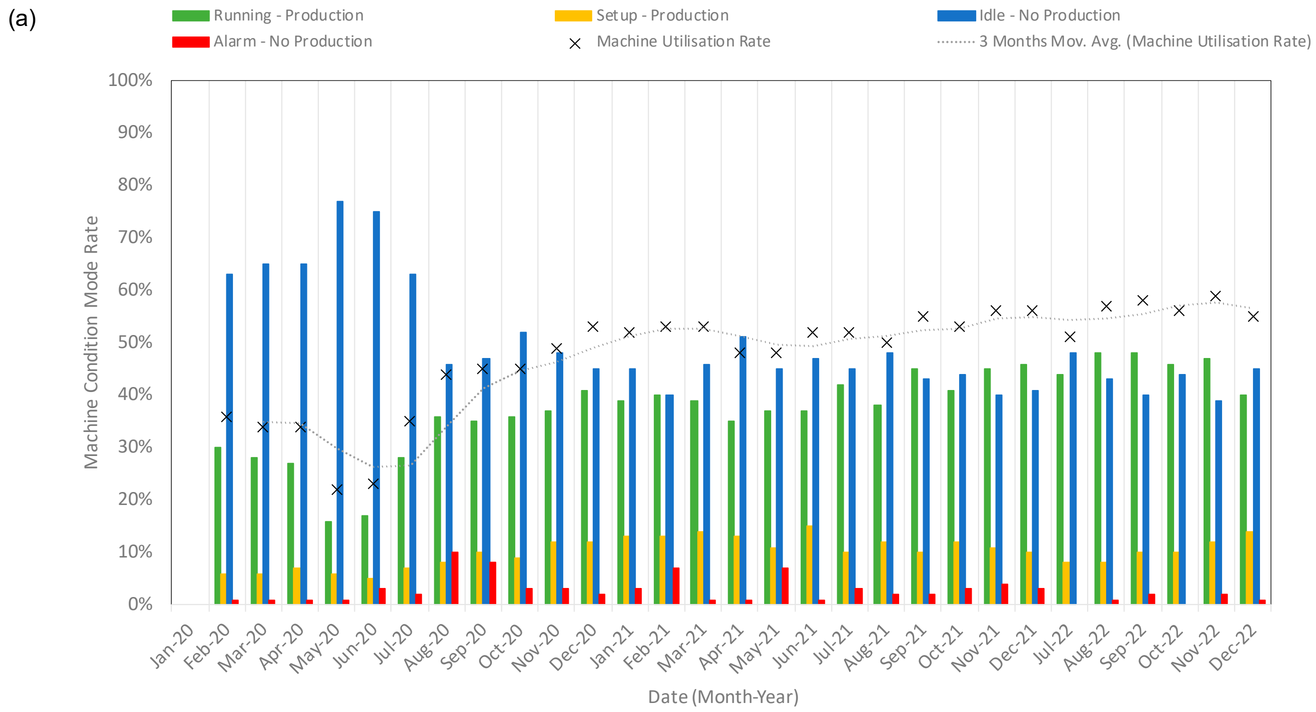
The four machine condition modes status are "Running", "Setup", "Idle" and "Alarm". Running and Setup modes occur when the machines are in production, i.e., the machine is either cutting steel or its tools are being setup to perform the required scheduled job. The Idle and Alarm modes status occur when the machines are not in production, i.e., the machine is stopped due to unscheduled downtime or breakdown.

The machine availability is the total machines available time calculated based on the total number of days per month the machines in the factory were available for production during the factory opening hours (including day and night shifts) and had production orders scheduled with labor resources to operate the machines. The graph also shows a plot of the machine use rate (Equation (3)), which is the ratio of the machines' time in production mode (Running + Setup) against the total machine availability time.

$$\text{Machine Condition Mode Rate} = \sum\left(\frac{\text{Machine Condition Mode}}{\text{Machine Availability}}\right) \tag{1}$$

$$\begin{aligned}\text{Machine Availibility (per month)} \\ &= \sum((\text{No. of days machines available for production}) \\ &\times(\text{No. of machines available for production}) \\ &\times(\text{Factory opening hours per day}))\end{aligned} \tag{2}$$

$$\text{Machine Utilization Rate} = \sum\left(\frac{\text{Machines in Production Mode (Running+Setup)}}{\text{Machine Availability}}\right) \quad (3)$$



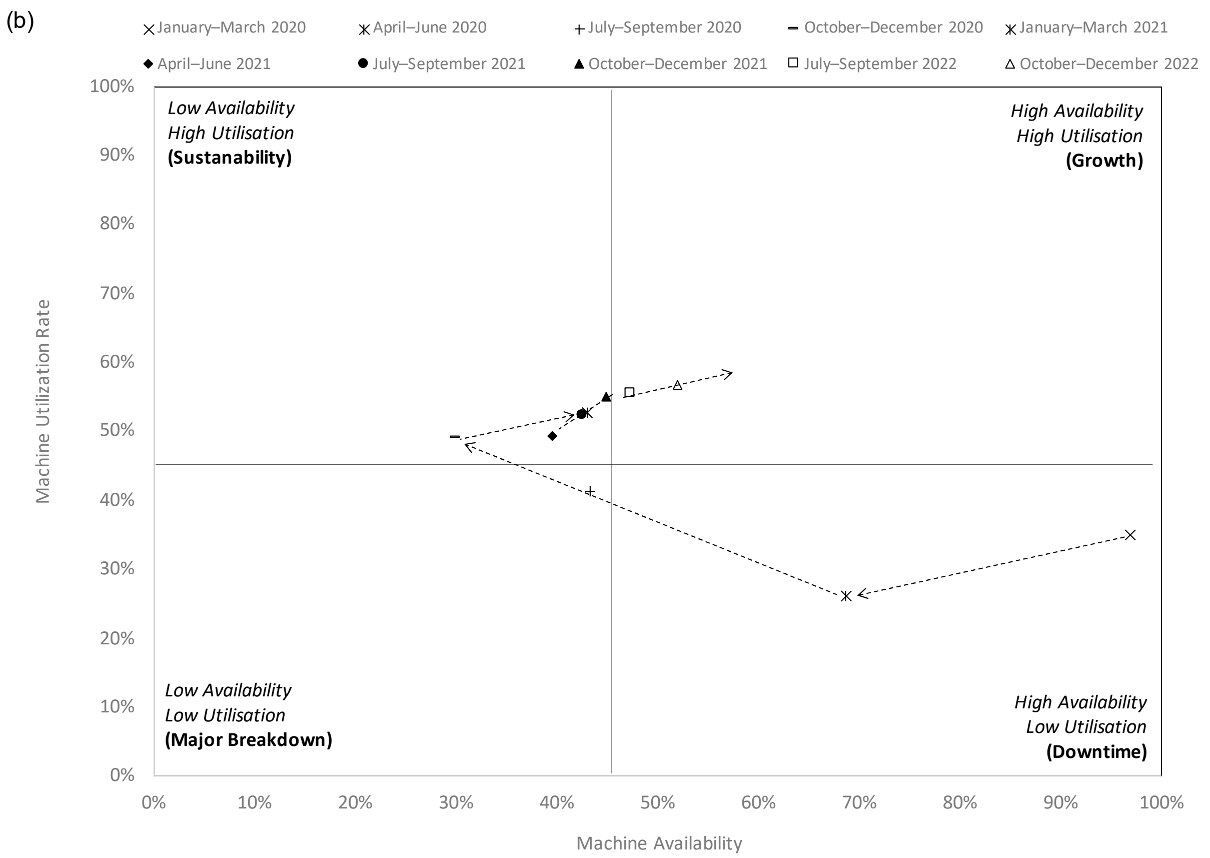


Figure 8. Productivity of the CNC machines in the factory over a period of three years (February 2020–December 2022): (**a**) machine condition status; (**b**) productivity map.

Figure 8a also shows a line plot of a three-month moving average of the machines' utilization. The machines' utilization rate in 2020 was 37.5% on average. In the first half of the year in 2020, February to June, the machine used rate was the lowest in the full three-year period, with M = 30% (SD = 6%). This was due to the combination of a high non-production mode (Idle) status and a low production mode (Running) status. In the second half of 2020, July to December, the machine use rate had increased with M = 45% (SD = 6%), which was due to a drop in the non-production mode (Idle) status, alongside an increase in the production modes (running and setup) status.

In 2021, the machines' utilization rate continued to rise to 52.5% on average. In the first half of 2021, January to June, the machines' utilization rate increased, with M = 51% (SD = 2.4%) but with reduced variance compared to that in 2020. In the second half of 2021, July to December, the machines' utilization rate further increased with M = 54% (SD = 2.4%) whilst maintaining a low variance.

In the first half of 2022, the historic machine condition data were not available to be used for the purposes of this study because the data for that period were lost and not saved during a database migration. Historical data availability is crucial for performance analysis and predictive analytics studies; therefore, data storage maintenance is important as big data grow. This is a common challenge faced by SMEs; hence, a dedicated IT team or a cloud database management solution can mitigate such risks.

For the remaining half of 2022, July to December, the machines' utilization rate mean further increased to 56% (SD = 2.8%) with a relatively low variance. The data also showed that the production mode (Running) occurred than the non-production mode (Idle) status for the later period of 2022.

To look at the improvements made to the machines' utilization rate overtime from another prospective, it was mapped against the machines' availability time. Figure 8b shows a scatter plot productivity map of the machines' utilization rate (Equation (3)) averaged over a three-month period against the machines' availability (Equation (2)) for the full three-year period from February 2020 to December 2022.

The map is also divided into four sections. The "Loss" section on the bottom left indicates the area where both machines' availability and machines' utilization were low, defined by figures less than 45%. This section is associated with high losses in the factory due to a major breakdown, for example, production line breakdown as a result of an electric fault. The "Downtime" section on the bottom right is the area where machines' availability was high (>45%), and the machines' utilization was low (<45%). This section is associated with low productivity due to high downtime. The "Resilience" section on the top left is the area where machines' availability was low (<45%), and the machines' utilization was high (>45%). This section is associated with flexibility and agility due to high productivity despite the low availability of resources such as production orders and labor resources. The "Growth" section on the top right is the area where machines were highly available, and the machines' utilization was also high (both >45%). This section is associated with growth due to the high productivity and highly availability of production orders, labor resources, etc.

The first two quarters of 2020, January to March and April to June, were both in the middle regions of the "Downtime" section of the map. The last two quarters of 2022, July to September and October to December, showed a significant shift towards the border lines of the "Loss" section and the "Resilience" section of the map. In 2021, all four quarters were in the "Resilience" section of the map at the bottom area towards the "Growth" borderline. The last two quarters of 2022, July to September and October to December, were in the "Growth" section of the map.

Figure 9a shows a bar-line graph of the cost savings associated with downtime (i.e., lost productivity) for a total period of four years of actual data from 2019 to 2022 and two further predicted years of 2023 and 2024. The graph shows three bars for each year. The efficiency lost costs is the actual total time lost compared to the time set for the production order in its routing. The indirect time lost is the total unscheduled time lost due to non-production-related tasks. The rework time is the time is the time taken to rectify an initially non-conforming product. The associated cost was calculated based on the machining time cost rate, which was set to 60 GBP/h by the factory. For the purpose of this paper's analysis, it was assumed that the machining cost rate remained constant throughout the period analyzed.

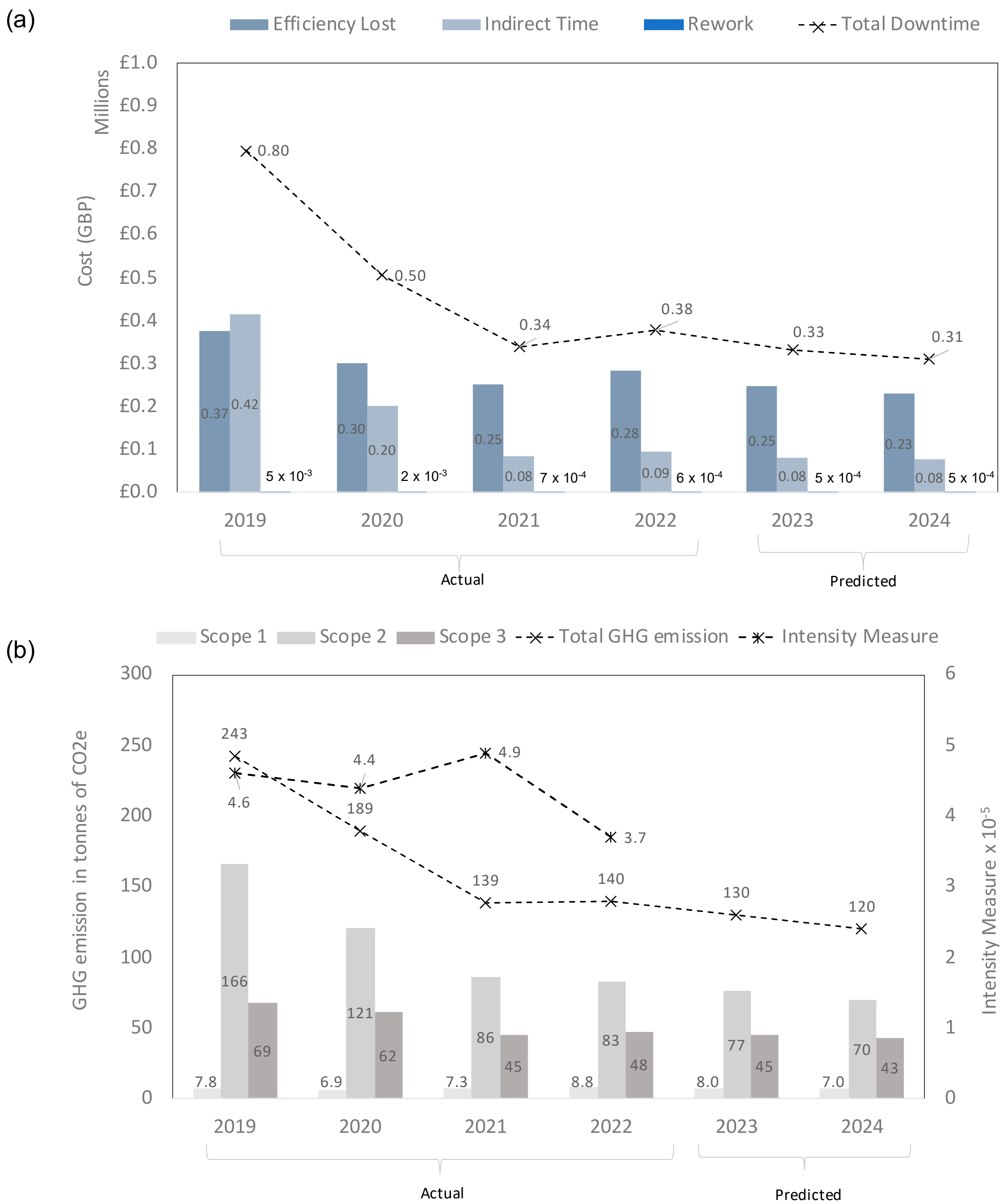


Figure 9. Productivity, financial, and environmental performance across six-year period (2019–2024): (**a**) total cost of downtime; (**b**) total GHG emissions.

Figure 9a also shows a line plot of the total downtime (efficiency lost + indirect time + rework) over the same period. In the year 2019, which was the base year, the total downtime was around GBP 800 K; this reduced significantly to GBP 500 K in 2020 and to GBP 340 K and GBP 380 K for 2021 and 2022, respectively. It was also predicted that the total downtime will be reduced by 12.5% in 2023 to GBP 330 K and further reduce by 6.25% in 2024 to GBP 310 K.

Figure 9b shows a bar-line graph of the environmental sustainability performance associated with the energy reduction and emissions for a total period of four years, from 2019 to 2022, and two predicted years, 2023 and 2024. The emissions' reduction was calculated based on the GHG emissions in tons of carbon dioxide equivalent (CO_2e). It is a KPI that measures the level of environmental emissions that affect the climate such as carbon dioxide (CO_2) emissions, which is the dominant one, but other GHGs also include methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF_6) and nitrogen trifluoride (NF_3).

The graph shows three bars for each year: Scope 1 included direct emission from sources that the company controls (e.g., burning oil and emissions from owned transport vehicles), Scope 2 included indirect emissions from energy purchases (e.g., electricity consumption from the grid), and Scope 3 included indirect emissions from sources up- and downstream of its value chain (e.g., employee computing, waste generated in operations, and water usage and treatment). The graph also shows a line plot of the total emissions (Scope 1+ Scope 2 + Scope 3) over the same period. In 2019 (base year), the total emissions was 242 tons of CO_2e; this was reduced to 189, 139, and 140 tons of CO_2e in 2020, 2021, and 2022, respectively. This was a total reduction of 42% in the emissions from the base year. It was also predicted that the total emissions will be further reduced by 7% each year to 130 and 120 tons of CO_2e, respectively, in 2023 and 2024.

Figure 9b also shows a second line plot of the intensity ratio measure (Equation (4)). The intensity measure is a common business financial ratio metric used in industry that is calculated based on the total tons of CO_2e per total GBP million of sales. Its gauges the emissions produced each year by the company based on the turnover generated in the same year. The turnover value was used instead of the actual volume of production output because it was difficult to measure the volume of the products produced each year due to the wide variety of products that were produced in small batches.

$$\text{Intensity Measure (per year)} = \frac{\text{Tons of CO2e produced}}{\text{Total GBP million of sales}} \tag{4}$$

In the base year 2019, the intensity measure was 4.6. It dropped to 4.4 in 2020 and rose to 4.9 in 2021. In 2022, the intensity measure dropped sharply again to 3.7. The relationship between both trendlines, the intensity measure and the total emissions, is further discussed in the next section.

4. Discussion

In this section, the results of the smart manufacturing application implementation are discussed, as is its impact on operational performance (productivity, machine utilization, and cost savings), economic benefits (financial investment opportunity), and environmental sustainability (energy and emission reductions). The summary of the impacts achieved by the precision manufacturing company over the years 2020 to 2022, compared with the base year 2019, are displayed in Table 1.

Table 1. Smart manufacturing application impacts over three-year period (2020–2022).

Operational Performance Impact: Productivity Improvements		Economic Benefit Impact: Financial Returns		Environmental Sustainability Impact: Emissions Reduction	
Machines' utilization improvements	47%	ROI	1 year	Total emission reductions	42%
Total downtime cost reduction	53%	IRR	40%	Scope 2 emission reductions	50%

This success can be attributed to the adoption of smart manufacturing practices and the implementation of the connectivity, integration, and analytics stages of the six-gear smart factory roadmap.

The connectivity stage focused on the factory floor's connectivity. It was achieved by connecting the CNC machines in the production lines through secure and resilient network to a condition monitoring system to ensure the real-time visibility of the machines and the machining process. As a result, this improved the machines' utilization through better production time management and improved maintenance management via the early identification of deviations to enable diagnostics.

The integration stage focused on the vertical integration of IT and OT. It was achieved by integrating the production management system, the ERP system, and the machine condition monitoring system through digital threads, which allowed production data to be exchanged relatively in real time across different functions at the office and on the factory floor. As a result, relevant processes that were predominantly managed by humans were digitized and automated, enabling full visibility of the production process and the factory environment and improving the capability to identify deviations and diagnostics related to the production process. All these contributed to productivity improvements, downtime reductions, and the minimizing of no-value-added activities, leading to time and cost savings.

The analytics stage focused on building enterprise intelligence. This was achieved by digitizing the data collection and reporting capabilities using a BI tool, where the business and production data collected from multiple sources across the enterprise and the factory floor were analyzed and reported relatively in real time. As a result, this enabled the visibility of KPIs relevant to the business to be accessed and monitored from one place as the source of truth as well as provided insights to enable quick problem identification and actions to be taken in order to adapt to changing needs, leading to agility improvements.

The impact of this implementation is evidenced in the improvements seen in the production machines' utilization, the reduction in the total downtime waste in the factory, the cost savings as a result of the total downtime reduction (i.e., lost productivity recovered), the financial investment returns with respect to return on investment (ROI) and the opportunity with respect to internal rate of return (IRR) of the smart manufacturing implementation, and the reductions in energy consumption and emissions in the operations over the three-year period.

The KPIs that were chosen in this study to evaluate the operational performance, economic benefits and environmental sustainability evaluation, are commonly used in the manufacturing industry and in the literature. In fact, the study by Maretto, et al. [25] on the real-life implementation of digital technologies within manufacturing and how such implementations have been evaluated in terms of operational performance and economic viability highlighted that the frequently adopted non-case-specific operational performance KPIs were related to process times efficiencies, resource utilization, cost, emission, energy consumption, and quality; however, their use was still quite low. That study also highlighted the scarcity of KPIs that can be used to evaluate industrial performance of industry 4.0 implementation in manufacturing and the need for academic attention. This study addresses this gap in the literature by evaluating the real-life operational performance KPIs used in the manufacturing industry. There is also a lack of economic evaluation in the literature, and there seems to be no standardized approach, with studies mainly focusing on a single indicator like cost or revenue, which is insufficient to provide a full picture of the actual economic impact of smart manufacturing applications in industry [20,25]. Therefore, the cost–benefit ROI and IRR analyses were proposed as the parameters of choice for economic evaluation.

4.1. Operational Performance Impact

The machines' utilization rate improved by 47% over the three-year period from 2020 to 2022. Prior 2020, there were no data available to evaluate the machines' condition status or how they had been utilized. In 2020, the mean machine utilization rate was 37.5%; this increased to 52.5% in 2021 and increased further to 56% in 2022.

As can be seen from Figure 8b, in the first half of 2020, the machines' utilization rate was low (<45%), and machines' availability was high (>70%), which reflected the reality of the underutilized CNC machines and low productivity in the factory. In late 2020, the machines' availability dropped significantly below 45% due to the impact of COVID-19 on the production orders and the labor resources available. However, in the second half of 2020 and in 2021, the machines' utilization rate increased to 45% and 52% on average, respectively, although the machines' availability stayed low (<45%) due to the limited resources, particularly labor resources during the COVID-19 period. The increase in the machine utilization rate in the second half of 2020 and in 2021 was due to better production time management by the machine operators, which resulted in improvements in productivity, which showed resilience during unstable times. In 2022, machines' availability continued to increase (>50%), as production orders became more sustained, and more people returned to work as COVID-19 restrictions eased. The machines' utilization rate continued to improv to 56% on average, a further improvement from 2021, resulting in more productivity and showing signs of potential growth.

The factory total downtime cost was reduced by 53% over the three-year period from 2020 to 2022 compared to the base year 2019. As seen in Figure 9a, the total downtime in 2019 was approximately GBP 800 K, the downtime was reduced by 38% in 2020 to GBP 500 K, and dropped by a further 32% in 2021 to GBP 340 K. In 2022, post-COVID-19, the total downtime increased slightly by 12% to GBP 380 K because of a ramp up in orders, particularly in new products of low volume, which required increased planning, testing, and evaluation. It was predicted that the total downtime would drop by 12.5% in 2023 and a further 6.25% in 2024 as the company further embedded a data-driven culture into its operations.

The reduction in the total downtime over the three-year period gave a total cost saving of GBP 420 K, which may have saved the business. The improvements to the machines' utilization over the three-year period resulted in productivity improvements. As a result, the factory was resilient during a challenging unstable industry period and showed signs of growth during more stable periods.

The access to live production data provided by the ecosystem of applications that formed the smart production management system in the factory also contributed to the productivity improvements, enabling quick responds and taking actions accordingly. For example, the machines' condition displayed by the Smooth Monitor AX dashboards enabled the maintenance engineer to respond quickly to potential breakdown alarms; the factory efficiency displayed by SMAS dashboards enabled the production manager to monitor production and unplanned downtime to respond quickly to any schedule changes' and the KPIs displayed by the Power BI dashboards enabled company managers to track the financial performance relatively in real time and react immediately when something was wrong.

4.2. Economic Benefits Impact

The economic benefits and financial impact demonstrated in Table 1 are based on the financial project investments made to fund the implementation of the connectivity, the integration, and the analytics stages of the smart factory roadmap and the returns it made as a result of the cost savings achieved from the total downtime cost reduction over the three-year period. The total return was 50%, and the ROI was within one year. The IRR was also calculated to quantify the merits of the investment opportunity and profitability over time, while considering the time value of money to compare projects that increase revenue or cut costs. The IRR over three-year period from 2020 to 2022 was around 40%, which showed a good profitable investment opportunity, achieved by reducing the overtime operational cost.

4.3. Environmental Sustainability Impact

The environmental impact demonstrated in Table 1 is based on the total emissions reduced and the Scope 2 emissions' reduction, related to energy reduction by the company over the three-year period from 2020 to 2022 compared with the base year 2019. Scope 2 emissions were reduced by 50% as a result of energy reduction, which led the total emissions to be reduced by 42% from the base year. The overall emissions' reduction was a significant milestone toward achieving the net zero carbon goal that has been set by the business and achieved through smart manufacturing.

The CNC production machines in the factory consumed around 90% of the total factory power consumption, followed by the compressors' consumption of 5%, and the remaining was distributed between the lights, network infrastructure, and other industrial or domestic appliances. The reduction in Scope 2 emissions was mostly due to lowered power consumption. The energy usage data collected from the current clamp sensor that w fitted onto the high-voltage panel board measured the total energy consumed in the factory, which were visually displayed with the condition status of the machines, which all contributed to knowing the following: (a) when the machines were running, (b) when more energy was used during the day/night or the weekend than previously thought, and (c) which machines that had been left on and which were consuming energy, so the engineers could then switch the individual machine off to save on energy and energy cost. This resulted in changed behaviors and better management of the power consumption in the factory, which contributed to the reduced energy consumption and, as a result, reductions in Scope 2 emissions.

As can be seen in the Figure 9b trend lines, the total emissions reduced by 22% in 2020, with a reduction in the intensity measure of 4%. Both having negative trends means that although production and sales have increased, the total emissions reduced due to reductions in all scopes of emissions, being mostly impacted by Scope 2, with a 27% reduction due lowered power consumption. In 2021, the total emissions were further reduced by 26%, but the intensity measure increased by 11% in the opposite direction, which means that the reduction in the total emissions was mainly due to decreased production and sales due to low machine availability and, as a result, lower power consumption. This was in line with the impact of COVID-19, where machine availability was low due to production orders falling and limited labor resources. However, in 2022, total emissions were very similar to the 2021 figures, but Scope 2 further reduced by 3.5%, and Scope 3 increased by 7% due to the waste generated as scrap because of the rapid ramp-up in new products introduced post-COVID-19. The intensity measure also significantly decreased by 25%, which means that although production and sales ramped up in 2022, the total emissions did not significantly increase from the previous year, with Scope 2 slightly reduced by 3%. This non-significant change in Scope 2 emissions was the result of sustaining the changed behaviors and the better power consumption management.

The environmental data also comprised the compressors' status and the temperature of the factory at different locations, providing an instant view of live and historical data. Monitoring such data was significant: it was discovered that production machines had been running for long periods on the backup compressor rather than the main compressor without this being realized; as a result, alerts were set up to notify engineers when the backup compressors automatically turned on when the main compressor was faulty [36].

Monitoring temperature changes and their effect on the quality of the product during machining is also an avenue that is being studied by tracking temperature to see if there is a risk of quality failures. Such information could help to set strategies with hard data justifying investing in cooling and ventilation systems in the factory or in areas where it is needed the most [36].

The outcomes of this study are as follows: Firstly, the actual business benefits realized as a result of smart manufacturing were significant: this study addresses the scarcity of research and the gaps in the literature of actual data regarding real-world industrial applications. Secondly, the practical application of the systematic six-gear roadmap approach for implementing smart manufacturing applications demonstrates that it is feasible in practice; this framework can be used as a strategic guide tool by the manufacturing industry to reduce the complexity of smart manufacturing deployments. Thirdly, the technical challenges and opportunities already discussed in Sections 2 and 3 and the limitations, optimization opportunities, and further development discussed in Section 6 all provide insightful information from a real-world practical implementation in industry. Such observations can be used to overcome obstacles to help achieve successful implementations when starting, scaling, or sustaining smart manufacturing applications in practice, especially in precision manufacturing. Finally, the overall outcomes of this study can be used as a case study to help reduce the internal barriers of smart manufacturing adoption in industry and catalyze industry 4.0.

5. Conclusions

The main contribution of this paper is the real-world practical implementation of smart manufacturing in a precision manufacturing SME using a systematic approach based on the six-gear smart factory roadmap, supported by the technical architecture of the implementation and the business benefits realized in terms of operational performance, economic benefits, and environmental sustainability.

This was achieved by applying the connectivity, integration, and analytics stages of the conceptual six-gear smart factory roadmap in practice to build a smart production management ecosystem using off-the-shelf technologies. The connectivity stage focused on the CNC machines' connectivity for real-time visibility of the machines and machining process. The integration stage focused on the vertical integration of IT and OT systems for production data to be exchanged in relative real time across different functions at the office and on the factory floor. The analytics stage focused on digitizing and automating the data collection, analysis, and reporting capabilities to improve the enterprise's business intelligence.

The business benefits and value created from this implementation were demonstrated using actual data related to productivity improvements and machines' utilization, reductions in downtime waste, cost savings, return on financial investments, and reduction om emissions from the operations over a three-year period, with data compared between before and after smart manufacturing application implementation. Over the three-year period from 2020 to 2022, the operational performance impacts were realized by improvements made to productivity through the machines' utilization rate (improved by 47%) and the reduction in the total factory downtime (reduced by 53%). The cost savings were realized as a result of the lost productivity recovered (GBP 420 K), which was potentially saved by the business. The economic performance impact was realized through the returns on financial investments through implementing the smart manufacturing application, which was returned within a year as a result of the direct savings due to improvements in productivity and downtime cost reductions. The IRR of 40% showed a good profitable investment opportunity in smart manufacturing, achieved by reducing the operational cost overtime. The environmental sustainability impact was realized by the reduction in the total emissions (reduced by 47%), mostly related to the reduction in Scope 2 emissions (reduced by 50%), as a result of energy consumption reductions, which were achieved by changing behaviors and better management of the power consumption of the factory. A significant milestone towards the net zero carbon goal was achieved through smart manufacturing.

The significance of this work is that it bridges the gap between theory and practice by practically applying the six-gear smart factory roadmap as a rapid tool that can be used as a strategic framework for implementing smart manufacturing applications in industry. The technical architecture discussed in this paper can serve as a technical guide for the practical implementation of smart manufacturing applications, which can help to reduce the complexity of development. Another significant aspect of this work is that it bridges the gap between academia and industry by showcasing the real-world actual business benefits realized from smart manufacturing, as well as the practical implementations, limitations, and opportunities of smart manufacturing applications in the precision manufacturing industry.

The value created and the impact realized in gaining a competitive advantage and driving environmental sustainability from smart manufacturing discussed in this paper can serve as a case study for academia and industry to help reduce the barriers to adoption and to accelerate the application of smart manufacturing, digital transformation initiatives, and industry 4.0 adoption, especially for SMEs, the backbone of the manufacturing industry.

6. Outlook on Future Work

This section outlines the limitations, opportunities for optimization, and outlooks for the further development of the connectivity, integration, and analytics stages of the roadmap discussed in this paper, including specific measure and expected effects. It also includes the scale stage to highlight other potential opportunities for implementing smart manufacturing applications relevant to industry.

6.1. Connectivity Stage

As more data are generated from machines, connectivity, maintenance, and diagnostics will become more important to the sustainability of production lines; therefore, proactive maintenance management applications will be required as they can further improve machines' utilization through the better management of unplanned downtime events such as machine failures, which further reduce downtime waste.

Such generated data are becoming the gold standard for OEMs because they can use them to optimize machine performance and their maintenance services. However, as big data grow, it becomes challenging for SMEs to maintain data storage as well as the IT infrastructure. SMEs can consider moving machine condition monitoring systems to the cloud through the software as a service (SaaS) model to overcome such data and system management challenges to mitigate the risks related to system maintenance, data security, and historical data loss. Furthermore, SaaS solutions in collaboration with OEMs are a good way forward to improve the maintenance services provided by the OEM, because such services reduce the challenges faced by SMEs and provide an additional revenue stream for OEMs by providing additional customer service. For example, the Mazak iConnect and Smart Cloud is an online connectivity and cloud service solution that provides highly secure connectivity and condition monitoring solutions for CNC machines [37]. This removes the burden of managing condition monitoring applications (i.e., Smooth Monitor AX) that are implemented in the connectivity stage, which can be hosted and managed in the cloud by the OEM. It can also include additional services provided by the OEM such as spindle performance diagnostics and machine diagnostics based on AI for predictive maintenance management. This SaaS cloud architecture is currently being piloted with Mazak as a part of the further optimization of the connectivity stage.

6.2. Integration Stage

As more smart manufacturing applications are implemented throughout the digital transformation and industry 4.0 journey, the IT, OT, and IIoT systems will grow and become part of the manufacturing system architecture, which, as a result, makes the vertical and horizontal integration of such systems even more complex. Significant challenges are associated with interoperability, scalability, and security as a result of the various digital threads needed to integrate these systems. However, connectivity and integration architectures and frameworks have further advanced over time to overcome system integration and data management challenges in order to avoid "data spaghetti", a term that refers to the various digital threads connecting and integrating systems in a non-systematic and a complex manner.

To address such challenges, the Unified Namespace (UNS) is a leading framework that serves as a single source of truth for all data and information across an enterprise through a structured, dynamic, and centralized environment where data from various sources (e.g., PLCs, SCADA systems, MES, ERP) are continuously updated and made accessible with greater scalability and security [38]. This framework paves the way for more connected and integrated data-driven enterprises, which are essential for a thriving industry 4.0. It is also a stepping stone towards advanced applications like AI and machine learning in manufacturing. It provides the necessary infrastructure for these technologies to access a wide range of data, learn from them, and offer real-time recommendations for process optimization. The UNS framework can potentially be used to optimize the integration stage by setting a centralized environment to collect and manage data collection from the IT/OT systems (e.g., Smooth Monitor AX, ERP, SMAS), IIoT sensors, and gateways on the factory floor, which can be shared when required using a common data transfer protocol, for example, the lightweight-based messaging protocol Message Queuing Telemetry Transport (MQTT) [39]. This overcomes the challenges associated with the direct connection and integration between each IT/OT system and gives flexibility in replacing or scaling systems without affecting the mechanics of data interoperability. If such measures are considered for the integration stage, this will shorten the time required for smart manufacturing applications to be implemented, and implementation costs will be reduced, which will speed up the value creation and the business benefits, which all contribute to reducing the barriers to the scaling of smart manufacturing applications.

Another limitation of this stage was the use of a technology solution provided by a start-up that lacked continuous support. The production management system "SMAS", which was implemented in the integration stage to orchestrate the data integration between the IT system "ERP" and the OT system "Smooth Monitor AX", was replaced by the time of writing this paper with another solution due to the solution provider closing, so they stopped supporting this solution. Technology solutions provided by start-ups are high-risk in the long term due to the unstable nature of start-ups; therefore, considering major technology solution providers with a history of providing well-maintained solutions is a smaller risk but comes with a cost. Another technology solution was recently introduced to replace the function of the production management system discussed in this paper with a cloud-SaaS-based solution with similar functions. Such implementation did not require significant changes to the data integration and connectivity architecture discussed in this paper but only to the data thread connections. This technology solution change can become common in the future in the smart manufacturing application market; therefore, considering a framework like the UNS for the data and system integration discussed earlier could reduce the complexity of system replacements and speed up new solution implementations.

6.3. Analytics Stage

As more data are generated from multiple manufacturing systems at the enterprise level and at the factory floor level, the BI tool (e.g., MS Power BI) hosted on the cloud will need to process and analyze the data to be translated into actionable KPIs to provide insights into deviation diagnoses, problem identification, and the identification of improvement opportunities, which will eventually help companies adapt to changing needs.

However, smart manufacturing is no longer just about finding ways to operate faster while reducing expenses; it is also about achieving this in a data-driven and intelligent way. Future work should consider utilizing big data with advanced algorithms and models (e.g., machine learning, deep learning, neural networks) to enable predictive analytics to transform manufacturing from being reactive to proactive. Instead of analytics that focuses on descriptive metrics and diagnostic analytics that explain why things have happened, the focus shifts to advanced analytics, "predictive and perspective intelligence-based analytics", which predict and find suggested patterns to enable actions to be taken. This will help to discover and reveal new answers to complex problems and can provide decision-based options, which will have a positive impact on operational performance and economic benefits.

The application of advanced analytics will also shift the gear to the fifth stage, "AI", of the smart factory roadmap discussed earlier in Figure 1. This can be achieved by empowering AI applications with advanced intelligent-based analytics that enhance capabilities such as perception, reasoning, continuous learning, and even autonomous decision making, transitioning the industry from automation to autonomy.

6.4. Scale Stage

Finally, scaling the implementation of smart manufacturing applications in a different area relevant to the strategic business objectives and needs can also be considered using the same systematic approach of the six-gear roadmap discussed in this paper. A practical application of another smart manufacturing implementation was investigated. As part of the strategy stage, the quality management and control capabilities were identified as potential areas for improvements that could be achieved through the application of smart manufacturing. In the connectivity and integration stages, an ecosystem of connected quality inspection machines integrated with a quality control management system was implemented. In the analytics stage, relevant quality KPIs and analytics were integrated with an enterprise business intelligence tool. As a result, significant improvements to quality planning, quality control, and inspection and quality reporting capabilities were realized over time, which had positive impacts on productivity, downtime cost savings, non-value-added time elimination, and scrap waste elimination [40]. Such work will be described in a publication in the future.

Author Contributions: A.T.S., conceptualization, methodology, investigation, data curation, writing—original draft preparation, writing—review and editing; B.M.A., review and editing, supervision, project administration, funding acquisition; O.J.M., data curation, review, and editing. All authors have read and agreed to the published version of the manuscript.

Funding: This work was funded by Innovate UK under grant No. 11153.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data is contained within the article.

Acknowledgments: The support of Beverston Engineering Ltd. and Liverpool John Moores University during this project is appreciated.

Conflicts of Interest: Author Oliver J. Miller was employed by the company Beverston Engineering Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

1. Al-Hassani, S.T.S. *1001 Inventions Muslim Heritage in Our World*, 2nd ed.; The Foundation for Science, Technology and Civilization (FSTC): Manchester, UK, 2006.
2. Schroeder, W. *Germany's Industry 4.0 Strategy, Rhine Capitalism in the Age of Digitisation*; Friedrich-Ebert-Stiftung (FES): London, UK, 2016.
3. Rahardjo, B.; Wang, F.-K.; Yeh, R.-H.; Chen, Y.-P. Lean Manufacturing in Industry 4.0: A Smart and Sustainable Manufacturing System. *Machines* **2023**, *11*, 72. [CrossRef]
4. Lorenz, R.; Buess, P.; Macuvele, J.; Friedli, T.; Netland, T.H. Lean and Digitalization—Contradictions or Complements? In *Advances in Production Management Systems. Production Management for the Factory of the Future: IFIP WG 5.7 International Conference, APMS 2019, Austin, TX, USA, 1–5 September 2019, Proceedings, Part I*; Springer International Publishing: Cham, Switzerland, 2019; pp. 77–84.
5. Klitou, D.; Conrads, J.; Rasmussen, M.; Probst, L.; Pedersen, B. *Germany Industrie 4.0*; European Union (EU) European Commission: Berlin, Germany, 2017.
6. *9th Annual State of Smart Manufacturing Report*; Rockwell Automation. Available online: https://www.rockwellautomation.com/en-us/capabilities/digital-transformation/state-of-smart-manufacturing.html (accessed on 2 December 2024).
7. Devonshire, J. *2024 Manufacturing Agility Report*; The Manufaturer. Available online: https://www.themanufacturer.com/reports-whitepapers/2024-manufacturing-agility-assessment/ (accessed on 2 December 2024).
8. Wellener, P.; Hardin, K. *2023 Manufacturing Industry Outlook*; Deloitte: London, UK, 2023.
9. *Global Manufacturing Prospects 2023*; KPMG. 2023. Available online: https://kpmg.com/de/en/home/insights/2023/03/global-manufacturing-prospects-2023.html (accessed on 5 March 2024).
10. Barriball, E.; George, K.; Marcos, I.; Radtke, P. *Jump-Starting Resilient and Reimagined Operations*; McKinsey & Company: New York, NY, USA, 11 May 2020.
11. pwc. COVID-19: What it means for industrial manufacturing. In *Research and Insights-COVID-19*; pwc: London, UK, 2020.
12. Countryman, T.; Rasmus, R.; McKinney, J.; Diaz, M.F. COVID-19: Adapting manufacturing operations to new normal. In *Insights: COVID-19: Supply Chain & Operations*; Accenture: Berlin, Germany, 2020.
13. Forth, P.; Laubier, R.d.; Chakraborty, S.; Charanya, T.; Magagnoli, M. *Performance and Innovation Are Rewards of Digital Transformation*; Boston Consulting Group: Boston, MA, USA, 2021; Available online: https://www.bcg.com/publications/2021/performance-and-innovation-are-the-rewards-of-digital-transformation-programs (accessed on 5 March 2024).
14. Commission, E.; Innovation, D.-G.f.R.; Breque, M.; De Nul, L.; Petridis, A. *Industry 5.0: Towards a Sustainable, Human-Centric and Resilient European Industry*; Publications Office: Luxembourg, 2021. [CrossRef]
15. Aheleroff, S.; Huang, H.; Xu, X.; Zhong, R.Y. Toward sustainability and resilience with Industry 4.0 and Industry 5.0. *Front. Manuf. Technol.* **2022**, *2*, 951643. [CrossRef]
16. Meehan, R. *Time for Industry 4.0: The Next Stage in the Data Revolution*; Inawisdom: London, UK, 2022.

17. Elnadi, M.; Abdallah, Y.O. Industry 4.0: Critical investigations and synthesis of key findings. *Manag. Rev. Q.* **2024**, *74*, 711–744. [CrossRef]
18. *State of Dgital Transformation-Bridging the Digital Divide*; TEKsystems, Inc.: Addison, TX, USA. Available online: https://www.teksystems.com/en-gb/insights/article/state-of-digital-transformation-bridging-the-digital-divide (accessed on 15 November 2024).
19. Devonshire, J. Now Hiring-Understanding and Tackling the Skills Shortage in UK Manufacturing. Available online: https://www.themanufacturer.com/articles/new-report-reveals-extent-of-uk-manufacturings-skills-shortage/ (accessed on 15 November 2024).
20. Ivanov, D.; Tang, C.S.; Dolgui, A.; Battini, D.; Das, A. Researchers' perspectives on Industry 4.0: Multi-disciplinary analysis and opportunities for operations management. *Int. J. Prod. Res.* **2021**, *59*, 2055–2078. [CrossRef]
21. Jurgens, J.; Gin, B.S. *The Global Smart Industry Readiness Index Initiative: Manufacturing Transformation Insights Report 2022*; Singapore International Centre for Industrial Transformation (INCIT): Singapore, 2022.
22. EDB. *The Smart Industry Readuness Index-Catalysing the Transformation of Manufacturing*; Singapore International Centre for Industrial Transformation (INCIT): Singapore, 2020.
23. Schuh, G.; Anderl, R.; Dumitrescu, R.; Krüger, A.; Hompel, M.T. *Industrie 4.0 Maturity Index-Managing the Digital Transformation of Companies*; Acatech National Academy of Science and Engineering: Munich, Germany, 2020.
24. Müller, J.M.; Islam, N.; Kazantsev, N.; Romanello, R.; Olivera, G.; Das, D.; Hamzeh, R. Barriers and Enablers for Industry 4.0 in SMEs: A Combined Integration Framework. *IEEE Trans. Eng. Manag.* **2024**, 1–13. [CrossRef]
25. Maretto, L.; Faccio, M.; Battini, D. The adoption of digital technologies in the manufacturing world and their evaluation: A systematic review of real-life case studies and future research agenda. *J. Manuf. Syst.* **2023**, *68*, 576–600. [CrossRef]
26. Arcidiacono, F.; Schupp, F. Investigating the impact of smart manufacturing on firms' operational and financial performance. *J. Manuf. Technol. Manag.* **2024**, *35*, 458–479. [CrossRef]
27. Saleem, A.; Sun, H.; Aslam, J.; Kim, Y. Impact of smart factory adoption on manufacturing performance and sustainability: An empirical analysis. *Bus. Process Manag. J.* 2024; *ahead-of-print*. [CrossRef]
28. Sufian, A.T.; Abdullah, B.M.; Ateeq, M.; Wah, R.; Clements, D. Six-Gear Roadmap towards the Smart Factory. *Appl. Sci.* **2021**, *11*, 3568. [CrossRef]
29. KTN. KTP Helps Embed Industry 4.0 Techniques to Transform Business Visibility and Efficiency. Available online: https://www.ktp-uk.org/case-study/ktp-helps-embed-industry-4-0-techniques-to-transform-business-visibility-and-efficiency-for-beverston-engineering/#:~:text=The%20aim%20of%20the%20KTP%20project%20is%20to,the%20next%20generation%20of%20smart%20production%20management%20systems. (accessed on 14 February 2024).
30. MadeSmarter. Beverston Engineering Building a Brighter Future. Available online: https://www.madesmarter.uk/resources/case-study-beverston-engineering/ (accessed on 14 February 2024).
31. *ANSI/ISA-95*; Enterprise-Control System Integration. ISA: Research Triangle Park, NC, USA, 2010.
32. Hankel, M.; Rexroth, B. The reference architectural model industrie 4.0 (rami 4.0). *Zvei* **2015**, *2*, 4–9.
33. Mazak, Y. Mazak iSMART Factory. Available online: https://www.mazakeu.co.uk/mazak-ismart-factory/ (accessed on 29 January 2024).
34. Cisco. *The Ultimate Guide to Smart Manufacturing*; Cisco: San Jose, CA, USA, 2018.
35. MTConnect_Institute. MTConnect Standard (ANSI/MTC1.4-2018). The Association for Manufacturing Technology. Available online: https://www.mtconnect.org/ (accessed on 5 March 2024).
36. Brainboxes. Measuring Energy in Precision Engineering. Available online: https://www.brainboxes.com/case-study/measuring-energy-in-precision-engineering (accessed on 11 January 2024).
37. Machinery&Manufacturing. TALKING TECH: Mazak iCONNECT–Industry 4.0 in Practical Format. Available online: https://machineryandmanufacturing.com/talking-tech-mazak-iconnect-industry-4-0-in-practical-format/ (accessed on 12 January 2024).
38. HiveMQ. Unified Namespace (UNS) Essentials. HiveMQ. Available online: https://www.hivemq.com/mqtt/unified-namespace-uns-essentials-iiot-industry-40/ (accessed on 28 May 2024).
39. HiveMQ. Modernizing the Manufacturing Industry with MQTT. Available online: https://www.hivemq.com/resources/modernizing-the-manufacturing-industry/ (accessed on 28 May 2024).
40. MadeSmarter. Case Study-Beverston Engineering Revisit Smart Factory Sucess. Available online: https://www.madesmarter.uk/resources/case-study-beverston-engineering-revisit/ (accessed on 28 May 2024).