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Digital transformation and business intelligence for a SME: systems thinking action research using PrOH modelling

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Abstract

This paper discusses the digital transformation journey of a small and medium enterprise (SME) based in the UK. With the proposed digital transformation archetype, the paper highlights the improvement in various key performance indices (KPIs) for the case SME. The core KPIs and operational KPIs show improvement through the technology adoption as part of the digital manufacturing initiative. While embracing technology, such as Industry 4.0, it is important to highlight the importance of the change and other benefits of technological changes. The paper uses socio-technological system principles to achieve a successful transition. An action research approach and a specific soft system thinking methodology known as Process-Oriented Holonic (PrOH) modeling were used in this paper. A digital twin architecture is presented in the paper that showcases the use of integrated technologies for a digital manufacturing roadmap.

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Keywords: System thinking; digital twin; digital manufacturing; virtual reality; action research

1. Introduction

1.1. Purpose

With more focus on customers, the new digital technologies and data analytics capabilities could be handy to meet their expectations. The technology adoption is critical to an organization's ability to be more competitive [1]. For

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small and medium enterprises (SMEs), there are hidden inefficiencies that force them to consider the vital role of Information Communication Technology (ICT) in business growth [2]. Gareeb and Naicker [3] have highlighted that digital technologies could help SMEs to be more sustainable from all three dimensions- economic, environmental, and social. Thus, it is imperative for SMEs to adopt digital technologies in their operations [4]. In this paper, we present a framework of digital transformation for a small and medium-sized manufacturing company in the UK. This was a successful attempt to improve lean Six-Sigma practices through digitalization. This paper aimed to see digitalization as a tool to improve lean practices for SMEs. In achieving this, we answered some of the research questions: (i) how digitalization can improve six-sigma lean practices observed through some of the key performance indicators; (ii) how to effectively digitalize operations in practice for managers; (iii) how to effectively communicate the change management through insights; and, (iv) how lean six-sigma principles can be considered as a part of a socio-technical system.

1.2. Background: the case description

The case company, Metal Assemblies Ltd. (MAL), in this paper, is based in the West Midlands area of the UK. The manufacturing company produces stampings and assemblies for their customers who predominantly serve the automotive industry. MAL has been in the business for about 70 years. Its customers are high-volume first-tier suppliers to mainstream prestige automotive OEMs. The company's manufacturing strategy has recently been changed from traditional to more technology-led manufacturing. In their efforts to bring that change, the project sought solutions that would benefit MAL. In this project, we focused on their journey of digital transformation. There are three phases of digital transformation: digitization, digitalization, and digital transformation [5]. This project aimed to achieve, in part, digitalization commensurate with industry 4.0 level of digitalization.

The Covid-19 crisis and the Russian-Ukrainian conflict have disrupted the supply chains of the automotive industry. And it can be reflected in the SMEs' demand patterns [6]. The SMEs would have no choice but to adapt their business models and strategies in response to increasing inflation, associated uncertainty, and the possibility of a recession [7]. One of the solutions to recover from this crisis is to boost the productivity and sustainability of SMEs [8]. In this case, the data serves as an invaluable asset to capture the demand, make changes in production, and use the limited responses effectively [9]. Without accurate up-to-date data, lean management is difficult to practice, as accurate data-driven decisions and quality issues cannot be detected [10].

Digital transformation is "a change in all job and income creation strategies, application of a flexible management model standing against competition, quickly meeting changing demands, a process of reinventing a business to digitize operations and formulate extended supply chain relationships; functional use of internet in design, manufacturing, marketing, selling, presenting and is data-based management model" [11]. The digital transformation can be seen as a process of rearrangement of technology, business models, and processes to create/co-create values for customers and employees. The pace of this transformation is determined by the consumer's demand. The process of transformation provides a productivity growth plan for SMEs and lowers their operating cost [12].

2. Literature Review: digital manufacturing

Traditionally, digital transformation has been considered as a change in a single manufacturing process [13]. The need of the hour is to bring that change in an integrated way to develop a seamless production system that embraces technology at every level [13]. With the fourth industrial revolution, or Industry 4.0, it is possible to create an intelligent, connected, and decentralized production system. This aligns with business owners' ambition to be the leader in adapting technology as a regulation of a product life cycle and value chain. There are many developments in terms of technologies that serve the purpose of being more competitive. The technologies such as robotics and automation, additive manufacturing or 3D printing, etc. These technologies are changing the business models for the SMEs making them innovative [14].

Emerging technologies are key to success for manufacturing companies. Many companies are using various technologies in silos in their efforts of transforming their operations digitally. The challenges imposed on the SMEs due to the uncertain supply and demand are mitigated by adopting digital technologies. The manufacturing firms are welcoming the change under the umbrella of Industry 4.0 adoption [15]. With Industry 4.0 adoption, it would be possible for manufacturing companies to not only deal with uncertainties but also enable data-driven manufacturing processes such as flexible manufacturing [16]. The manufacturing sector has seen an evolution from what it was in the 1980s in the form of Computer Integrated Manufacturing (CIM), where computers were operating machines effectively, and that way reducing the cost of production [17, 18]. Manufacturing science is no longer unidirectional, but it is a multidisciplinary organizational science involving Lean Manufacturing, Total Quality Management, Six Sigma, and Concurrent Engineering [18, 19].

Lean production, derived from the Toyota Production System (TPS), aims to eliminate waste from operational processes. Six Sigma, a quality methodology derived from Motorola's quality management system, aims to make processes increasingly error-free by identifying and controlling assignable causes that affect the variability of production output. Together lean and six-sigma principles, driven by customer demands and innovative enterprise strategy, can improve digital capability [20] and vice versa. Attempts to eliminate waste and reduce errors show that ongoing lean-six-sigma is not easy [21] and therefore it is vital to create a supportive leadership environment and a culture of continuous improvement [22]. In addition, high-velocity data-rich systems can facilitate quick decision-making for monitoring and reacting to changing production scenarios through digitalization strategies - where digitalization is the process of moving towards Industry 4.0 principles.

Clegg [23] states that careful measurement and selection of lean-six-sigma projects are critical to improve lean practice and reduce errors; and in this project, further attention was given to lean Six Sigma project selection to ensure that also facilitated the implementation of Industry 4.0 digital technologies. Lean-six-sigma projects are based on the DMAIC (Define, Measure, Analyse, Improve, and Control) cycles - similar in many ways to Deming's (1986) PDCA (Plan-Do-Check-Act) cycles. In this project, PDCA cycles have been carefully chosen to focus on different aspects of digitization in the case company.

2.1. Digital twin

The digital twin is the virtual representation of a physical object or system across its unique lifecycle. The digital twin is an integral part of smart manufacturing and its sustainable business model [24]. The digital twin effectively uses the real-time data from multiple resources to intrinsically enable learning, reasoning, and contributing to extracting actionable insights [25]. It is also seen as an integrated simulation of a complex system that mirrors its corresponding twin [26]. A digital twin has three major parts: Physical part, Virtual part, and Connecting data that tie the physical and virtual parts together [27]. Tao [27] provided some of the characteristics of a digital twin:

- Real-time reflection- the physical and virtual spaces exist in a digital twin. Virtual space is a highly synchronized, multi-fidelity model that reflects the real system.
- Interaction and convergence. This characteristic can be explained by three aspects.
  - A fully integrated digital twin where the data flow is integrated throughout the system.
  - Use of historical data and real-time data for insightful decision-making with experts' knowledge.
  - The data exchange between the physical system and the virtual one.
- Self-evolution- a completely autonomous system where artificial intelligence and machine learning can drive the system autonomously.

By combining the classification of digital twins by level of data integration and organizational scope we can see that the concept covers a wide range of applications (see Fig. 1).

In the context of the organization, the scope of a digital twin can be at the product, process, and enterprise level. At the product level, this type of digital twins relates to the emulation of physical objects such as machines, vehicles, people, and energy (e.g. autonomous vehicles). They can be considered as an extension of computer-aided design (CAD) and computer-aided engineering systems, which capture data that can then be used to detect issues and generate information that can be used to improve performance. They often have a focus on improving the efficiency of product life-cycle management, which is important for successful product-as-a-service or Servitization [28] business models. Digital twins allow the monitoring of multiple products and resources in different operating conditions and different geographic locations.

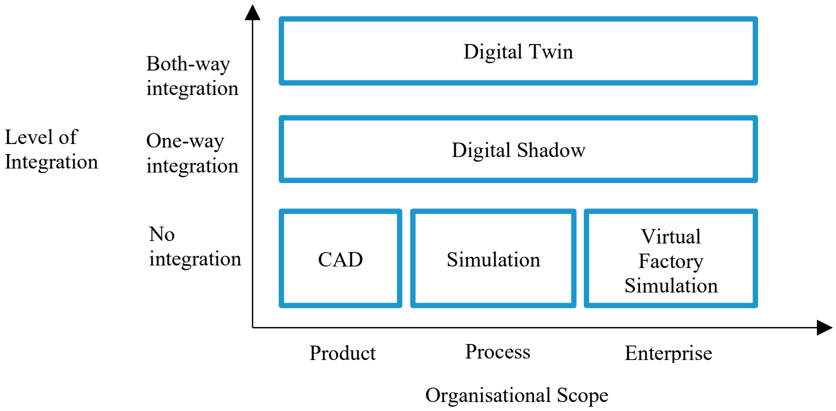


Fig. 1. Level of data integration and organizational scope of a digital twin [29]

A digital twin at the process level emulates processes over time and so requires a simulation environment, i.e. any of the simulation methods (discrete event simulation, agent-based simulation, and/or system dynamics simulation) or simply a gamification environment (e.g. modelfactory@SIMTech). One application area is a tool change-over process. Here a simulation/gamification model provides a virtual representation in real time of the manufacturing process through data connections over the IoT. The status of the machine and other resources could be on the operator's smart devices, i.e. tablets, and virtual reality (VR) sets. A machine-learning algorithm is used to provide a prediction of the remaining useful life of the manufacturing equipment based on its current usage and historical data of the process. The digital twin can be run into the future and predict machine failure based on its current status and scheduled future usage. The digital twin can then communicate back to the equipment to instigate a maintenance operation at the appropriate time. The digital twin thus provides an intelligent and automated predictive maintenance capability.

At the enterprise level, enterprise simulations aim to evaluate decisions made anywhere in the company on the performance of the whole business [30]. Enterprise digital twins can be implemented by using multiple digital twins that are in use at the process level (e.g. digital supply chain). Applications include the connection of the digital twin to an enterprise resource planning (ERP) system in order to improve factory scheduling to reduce waste and management of inventory.

In terms of the level of data integration, there are three possible levels of integration between the simulation and its real-world object counterpart (see Table 1). When there is no automated data exchange between the simulation and the real-world object, when there is an automated one-way data flow from the real-world object which leads to a change in the state of the simulation, and when data flows fully integrated in both directions. These one-way digital twins may be referred to as Digital Shadows [31]. Digital twins require a two-way data flow to provide a control capability to act in response to predicted behavior. Corrective actions are often implemented using analytics methods based on machine-learning algorithms that provide appropriate methods of process control actuation.

Table 1. Level of integration of a digital twin

ONGGO [32]	KRITZINGER [33]	DESCRIPTION
Type 1 (DSS)	No Way	A copy but not updated in real-time.
Type 2 (Control)	1 Way	Physical system sends data to the simulation. For type 1 a decision maker controls the physical system.
Type 3 (OpenLoop)	2 Way	Data flow in both directions. The simulation controls the physical system with an actuator.

In general, the level of complexity required for the simulation increases for a wider level of scope and for the level of integration. The development of digital twins with fully integrated data flows in both directions is complex and is still in its infancy.

3. Methodology: system thinking and action research

The methodology used in this paper is action research, specifically the soft system approach known as Process-Oriented Holistic (PrOH) modeling. As change management is one of the critical factors for a digital transformation and thus for the creating a digital twin, an action research approach makes complete sense to facilitate the change [34, 35]. Through PrOH modeling, it is possible to redesign the business processes that will lead to a successful digital transformation [35]. Also, with implementation of digital twin, it was expected that it would bring cultural change for the case company, and thus PrOH modeling was chosen as a methodology. The drawbacks of conventional process mapping techniques are overcome by PrOH modeling, where the modeler can develop feedback loops to elicit the intangible system factors [36]. There are many advantages of using PrOH modeling in the socio-technical setting of systems, where the operations can be conceptualized, visualized, and analysed with feedback loops [37, 38]. The PrOH modeling is considered relevant for manufacturing operations trying to successfully implement Industry 4.0 technologies to become leaner [39]. In explicating the hidden and emergent properties of systems, subsystems, and meta-systems, PrOH Modelling offers an appropriate means of visualizing processes in a people-centered system under observation.

We present a PrOH model at a high strategic level for the industry partners in the project, i.e. MAL Delivers Pressed Metal Parts. We constructed four PrOH models for the mid-level or tactical level; (in sequence) ‘Win Customer Orders’, ‘Establish Advanced Product Quality Planning (APQP)’, ‘Manufacture Finished Metal Pressing’, ‘Ship Finished Metal Pressings’. Two further models were constructed at a lower or operational level for the ‘Establish APQP’ tactical model: namely ‘Machine Setter Produces First-Off Production’ and ‘Machine Operator produces last-off Steel Parts’. Each of these models is constructed as a holon (a system that is quasi-autonomous) and is part of a set of models known as a holarchy.

3.1. Timeline of industry 4.0 implementation

Fig. 2 shows the timeline for the Industry 4.0 implementation for MAL. This timeline highlights technical events where new devices and software were implemented. The timeline also depicts other key events in the project, such as training, analysis, modeling, process change, and strategic and cultural change. We realized improvements in the key performance matrices throughout the duration of the project. These metrics are synonymous with lean and Six Sigma metrics, i.e. changeover times, OEE (or Overall Equipment Efficiency). Each PDCA/DMAIC cycle was delivered as an interdependent quasi-autonomous sub-project within the overall systems thinking action research approach. The modeling followed the specific rules and guidelines of PrOH modeling [34].

The success criteria for the project was to be able to collect live data from different sources, such as Enterprise Resources Planning (ERP), Quality Management System (QMS), and Programmable Logic Controllers (PLCs) that are mounted on machines/resources. The live data is key to success as discussed in other research by Martinez [40]. These data sources were used to construct a digital dashboard. The intended purpose of the project was not only limited to the development of a digital dashboard but also to seek improvement through PDCA cycles to improve: strategic road mapping, organizational culture, semi-automated data collection, analytic methods, production planning, and hands-on shop floor training. The process of digitalization [41] and performance improvement, as deployed in this project, has been advocated by numerous studies [42, 43] and achieved the project objectives.

4. Findings and Discussion

4.1. Digital twin architecture

Fig. 3 demonstrates the digital twin architecture used for the project. There are five different streams of data that are gathered in the digital twin. Fig. 4 shows the operational level of data that is used in the digital twin. The operators feed into the Kapture.io (quality management system) tablets, where the data such as quality control checks, production recording, and non-standard operations is collected. The ERP data, such as sales orders, invoices, and BOM data is captured in MieTrakPro. The DECADE system is a load monitoring system for power presses, process monitoring, and a control system that is installed on each machine on the shop floor to gather production and operations data. It was also important to monitor each machine's performance and plan the maintenance effectively. The MaintainX collects the machine data through PLCs (programmable logic controllers). All the data is stored in a centralized data warehouse which is analyzed on a BI dashboard, (i.e. PowerBI).

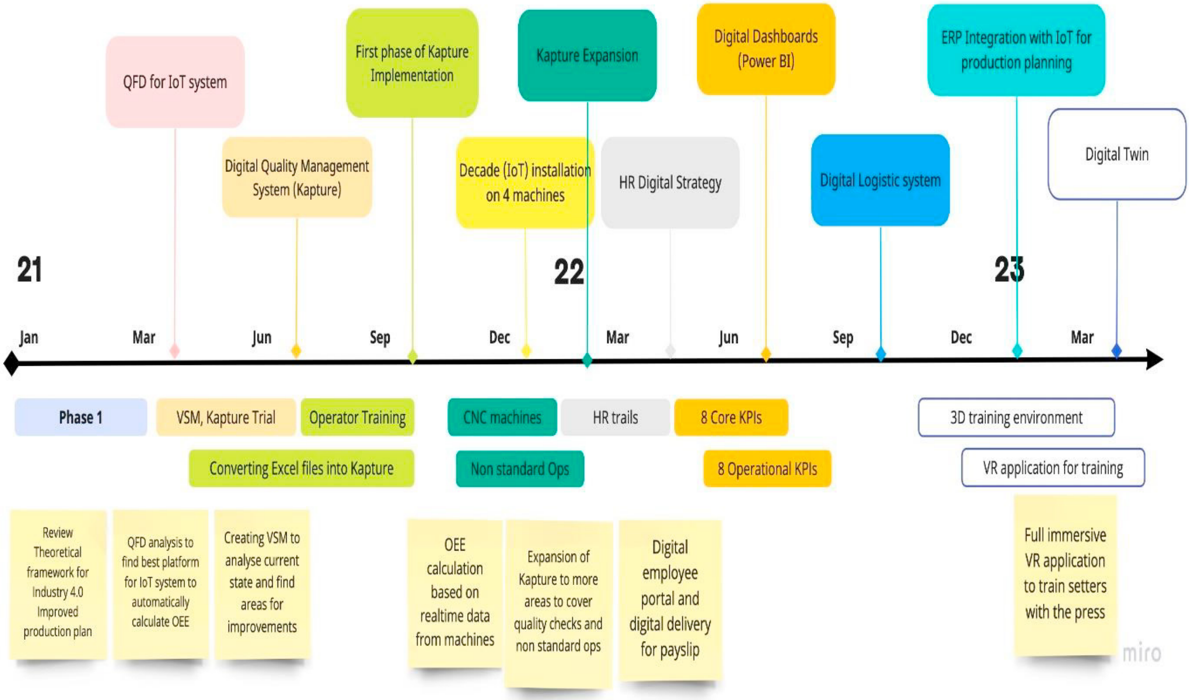


Fig. 2. Timeline of events in projects

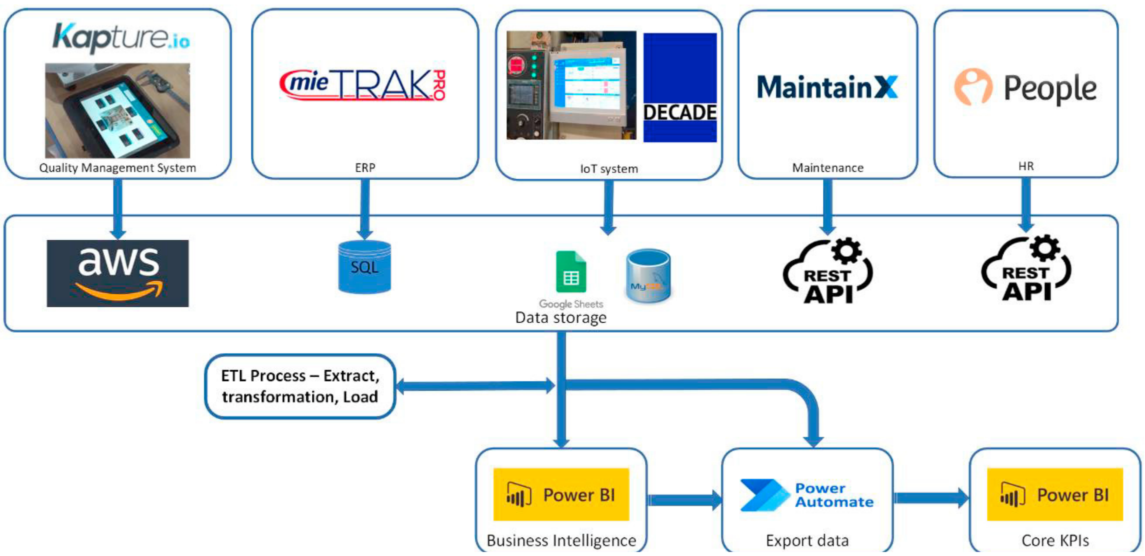


Fig. 3. Digital twin architecture

The digital twin has accelerated the analytical processes and empowered production planners in enhanced knowledge management practices, provided better data quality, improved technology readiness, and increased performance efficiency [44]. Specifically for MAL, digitalization primarily meant fixing PLCs to their press and folding machines gathering operational parameters (such as OEE, output, maintenance measures, etc.). The MAL's journey of digital transformation started with one press machine which then expanded to 11 other machines. The data could then be fed, via various cloud-based middleware systems into a PowerBI dashboard. With the PowerBI dashboard, various advanced analytics were performed in an integrated way. The Power BI dashboard meant that live data from this machine could be viewed in real-time, online, from anywhere in the world. In implementing Industry 4.0, it was also given due consideration to Industry 5.0 factoring human intelligence. The implementation of these changes was facilitated by the PrOH modeling methodology.

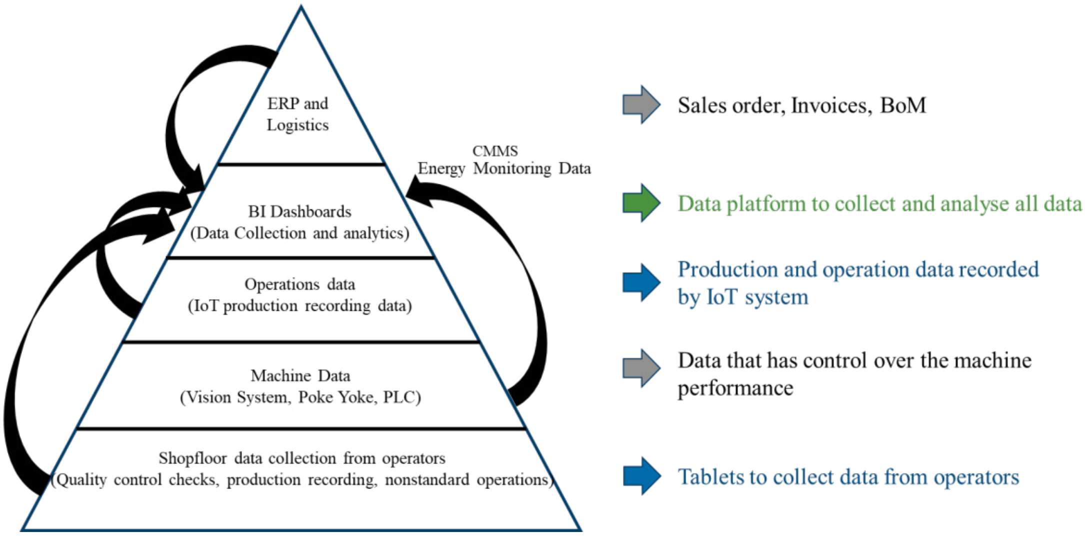


Fig. 4. Data flow or connection in the digital twin

4.2. KPI monitoring

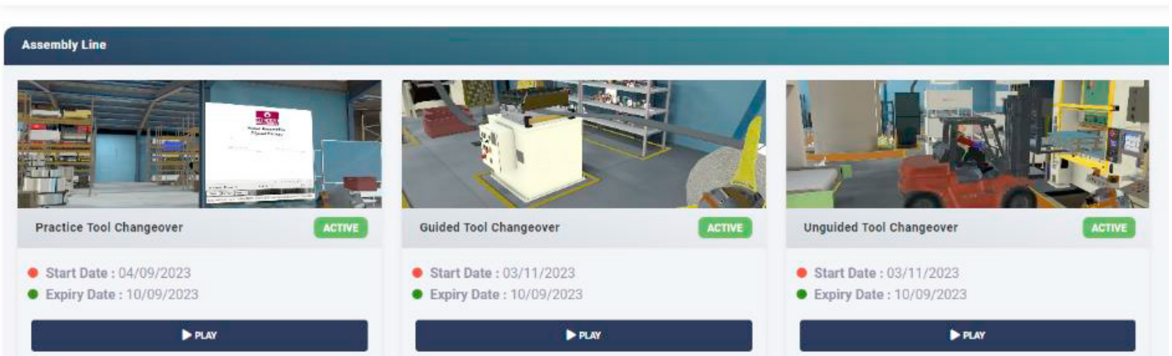
With the digital twin in the form of PowerBI, many key performance indicators were monitored throughout the project duration. Figure 5 is a snapshot of all the KPIs. Over the duration of the project, six cycles of plan-do-check-act (PDCA) were performed using the Socio-technical systems (STS) theory as a supportive theory. The STS theory is central to the KPI monitoring process. As acknowledged by the European Commission, while embarking on the journey of digital transformation, it is important to maintain human-centered manufacturing. This move will make manufacturing operations more resilient and sustainable [45, 46]. This also closely depicts what can be expected in the new industrial revolution, i.e. Industry 5.0.

4.3. Technologies development

Another aspect of digitalization addressed by this project, in addition to live data feeds, was the creation of a virtual digital environment. The whole production facility was scanned and turned into an interactive digital model. Again, as a pilot, the same press machine as detailed in Outcome 'i' was selected to be used as a trainer for the changeover of tooling to improve OEE. OEE was seen as a particular problem in the factory for a variety of reasons (e.g. heavy tooling, complex storage practice, safety reasons, high degree of casual labor use, etc.). Figure 6 presents the virtual digital trainer was developed in three modes (a) 'guided' mode (b) 'practice' mode, and (c) 'unguided' mode - each with increasing difficulty. In the unguided mode, the virtual simulator also has the digital dashboard visible in the virtual world. Therefore, it is possible for any MAL user to log to this virtual world factory to train themselves on the changeover process for a particular machine, and see real-time operational data for any machines connected via PLCs. This virtual world is also available to view as a 3D version in a MetaQuest virtual reality (VR) headset; which can be used to also train the trainees/students.

	2021				2022				2023	
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2
Core KPI										
Customer Concerns						Digitalised	20% increase due to better detection.			
Customer PPM						Digitalised	30% increase due to better detection.			
Internal PPM							Digitalised	Realtime data helped to address major issues and reduce internal PPM by 20%		
Health and Safety								Digitalised	Historical data helps to avoid repeatable accidents	
Transportation cost							Digitalised	Actual data showed performance was worst 10% increase due to better detection.		
Delivery Performance							Digitalised	20% improvement on time.		
Cost of Poor Quality				Digitalised	Live real data brought down this KPI as it was not captured accurately before. 30% improvement on time saving due to less rework.					
Direct Labour (Labour Efficiency)								Digitalised	10% reduction in cost of labour	
Operational KPI										
Operator Audit (Layered Audit)			Digitalised	50% improvement by identifying main issues						
Housekeeping (5S)					Digitalised	40% improvement by identifying main issues more quickly.				
OEE		Digitalised	Between 30% to 50% improvement							
Attendance								Digitalised	5% to 10% improvement	
Vendor rating			Digitalised	20% improvement time saving.						
Tooling Job Card (Maintenance)						Digitalised	30% improvement time saving			
Customer concern external cost						Digitalised	Increase visibility. 10% increase by time saving			
Scrap Cost				Digitalised	30% increase due to better detection with digital tools.					

Fig. 5. KPI measurements throughout the project timeline



a b c

Fig. 6. Desktop versions of the digital twin (a) Guided mode; (b) Practice mode; (c) Unguided mode

5. Conclusion

In this paper, we discussed the digital transformation journey of a SME. We presented the digital twin architecture that was used for the successful implementation of Industry 4.0. The digital twin is effectively operational for production planning and control. A 3D virtual environment is used to train new employees as well as for teaching to an academic audience. We highlighted the socio-technological system principles in the finding which is important from the new industrial revolution point of view, i.e. Industry 5.0. Embracing the human factor is critical for a sustainable and resilient digital manufacturing setup.

This paper adds value to the argument that it is possible to implement Industry 4.0 in an SME. This can be achieved by a system thinking approach, using PrOH modeling. The success story of this project will inspire many academics and practitioners.

The limitation of this study is that it uses only one in-depth two-year case study; however, this limitation will be addressed in further work, when increased abductive rationalization against socio-technical systems theory occurs.

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Note: the write-up of this project in this conference paper is kept brief, confidential and descriptive to allow a journal paper version to be written later without any accusation of self-plagiarism. The journal paper version will include more details on the action research and systems thinking methodology and abductive rationalization to lean thinking as a socio-technical system theory construct to generalize the in-depth findings from this case.

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