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An implementation model for digitisation of visual management to develop a smart manufacturing process

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Abstract

Purpose – This paper aims to introduce a model using a digital twin concept in a cold heading manufacturing and develop a digital visual management (VM) system using Lean overall equipment effectiveness (OEE) tool to enhance the process performance and establish Fourth Industrial Revolution (I4.0) platform in small and medium enterprises (SMEs).

Design/methodology/approach – This work utilised plan, do, check, act Lean methodology to create a digital twin of each machine in a smart manufacturing facility by taking the Lean tool OEE and digitally transforming it in the context of I4.0. To demonstrate the effectiveness of process digitisation, a case study was carried out at a manufacturing department to provide the data to the model and later validate synergy between Lean and I4.0 platform.

Findings – The OEE parameter can be increased by 10% using a proposed digital twin model with the introduction of a Level 0 into VM platform to clearly define the purpose of each data point gathered further replicate in projects across the value stream.

Research limitations/implications – The findings suggest that researchers should look beyond conversion of stored data into visualisations and predictive analytics to improve the model connectivity. The development of strong big data analytics capabilities in SMEs can be achieved by shortening the time between data gathering and impact on the model performance.

Originality/value – The novelty of this study is the application of OEE Lean tool in the smart manufacturing sector to allow SME organisations to introduce digitalisation on the back of structured and streamlined principles with well-defined end goals to reach the optimal OEE.

Keywords Industry 4.0, Visual management, Manufacturing process OEE, Digital transformation,

Paper type Research paper

Nomenclature

AI = Artificial Intelligence;
CH = Cold Heading;

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DMADV = Design, Measure, Analyse, Define, Validate;
DMAIC = Define, Measure, Analyse, Improve, Control;
ERP = Enterprise Resource Planning
HMI = Human Machine Interface;
I4.0 = Fourth Industrial Revolution;
IoT = Internet of things;
KPI = Key Performance Indicators;
OEE = Overall Equipment Effectiveness (A × P × Q);
A = Availability;
P = Performance;
Q = Quality;
PLC = Programmable Logic Controller;
PDCA = Plan, Do, Check, Act;
SME = Small and medium enterprises.
SMED = Single Minute Exchange of Dies;
TPM = Total Preventative Maintenance;
VM = Visual Management; and
VSM = Value Stream Map.

1. Introduction

Industrial revolutions have caused radical changes in the tools and production processes used by people. In these periods of time, new production methods and lifestyles can be formed by transforming the communication tools and production systems used. In the Fourth Industrial Revolution (I4.0), which is the current revolution, the use of the internet for intelligent networking of processes and machines became widespread and caused the explosion of the concept of Industry 4.0 (Mittal *et al.*, 2019; Zhong *et al.*, 2017). I4.0 can sometimes be viewed as an abstract entity, where different terms are used synonymously: smart manufacturing, internet of things (IoT), agile manufacturing, cyber physical, digitisation or advanced manufacturing. In other words, we associate the concept of I4.0 with the transformation of typical resources into intelligent objects which respond automatically when they sense, act and behave in a smart digital environment. One of the important developments brought by I4.0 is digitisation. The main purpose of digitisation is to merge the physical and virtual worlds, and to provide real-time visualisations on the status of the physical world. Digitisation represents a concept that aims to create a digital twin, that is, a digital representation of a physical object, that provides real-time information to improve and maintain performance (Torres *et al.*, 2020). I4.0 can offer organisations an effective method to enhance or establish Lean systems.

Previous research has recognised a strong interdependency between Lean and I4.0 (Tortorella and Fettermann, 2018; Rossini *et al.*, 2021). Indeed, Lean processes are seen as highly streamlined and structured with a goal of standardising work steps and times taken to carry out those steps, and to create a visual workspace, all of which can facilitate I4.0 implementation and automation (Kolberg and Zuhlke, 2015). Several other studies pointed out that I4.0 technologies can boost Lean systems framework (Buer *et al.*, 2018). The use of IoT, sensors and other smart technologies can enhance Kanban's and improve efficiencies of milk runs, and even shorten cycle times (Hofmann and Rusch, 2017). Moreover, the technologies associated with I4.0 can provide real-time data, which ultimately can be used to visually display the value stream in real time and make the detection of waste or abnormalities more efficient (Mrugalska and Wyrwicka, 2017). The success of I4.0

transformations strongly depend on the establishment of a positive synergy between Lean principles and digitisation.

Visual management (VM) is a well-defined Lean concept which starts with 5S and seeks to establish visual indicators and cues to prompt people to act or to notify them when an abnormal condition occurs, leading to visual control whereby abnormal conditions are prevented in advanced visual control systems (Ohno, 1988; Kurpjuweit *et al.*, 2019; Borkar and Rai, 2019). Indeed, VM can be viewed as a moderating factor within a Lean organisation (Van Assen and de Mast, 2019). Visual indicators can increase the operational process performance using key performance indicators (KPIs) and monitoring equipment output such as overall equipment effectiveness (OEE). Typically, information is presented on signboards, status boards or standard worksheets and a cross-functional team is tasked with manually updating information periodically (Jaca *et al.*, 2014; Eaidgah *et al.*, 2016). Research has demonstrated that VM can have an impact not only on performance but also on management practices of an organisation (Bititci *et al.*, 2016). The previous work reports barriers to the implementation of VM systems which are the lack of resources, complexity of underlying processes, organisational culture and resistance by shop floor personnel to changes in their daily routine (Kurpjuweit *et al.*, 2019). The main challenge with VM is related to inconsistencies across different organisations which are mostly caused by the lack of clarity in the conceptual understanding (Tezel *et al.*, 2016; Bateman *et al.*, 2016). Thus, VM should be conceptually understood as a supporting factor for other functions within the Lean organisation. Moreover, the previous work recommends understanding VM as a fitness factor rather than a standalone tool to achieve operational improvements (Tezel *et al.*, 2016). Visual technology is highlighted as one of the smart technologies which can significantly influence the shop floor management system. The options to visualise the VM system are related to use of maturity models (Murata and Katayama, 2016; Eaidgah *et al.*, 2016). However, very little research is available on digitising VM systems.

Maturity assessment models for an organisations I4.0 maturity were previously critically reviewed, Digital Readiness Assessment Maturity, Smart Manufacturing Readiness Level and Manufacturing Operations Management Capability Maturity Model and thus, indicated challenges which small and medium enterprises (SMEs) can be faced with by trying to achieve the requirements of these models when compared with larger organisations (Mittal *et al.*, 2019). The idea of a Level 0 is based on the results from the previous maturity models, where organisations had to take stock of where exactly they stand in terms of digitisation and I4.0, a reality check of sorts, before embarking on a transformation programme. The introduction of a Level 0 provides organisations with an opportunity to create a roadmap of how the I4.0 transformation can be achieved. This is an opportunity for organisations to have an open and transparent evaluation of where they are in terms of I4.0 readiness (D'Silva and Lawler, 2022). Ultimately organisations need to shorten the path between data and impact (Baskin, 2022).

This work aims to introduce a model using a digital twin concept at a manufacturing process and develop a digital VM system around OEE to enhance performance and develop I4.0 within the organisation. For the first time, this research will demonstrate that the likelihood of successful I4.0 transformations can be greatly increased when focused on Lean tools, which are well defined and structured. The OEE will be considered as a traditional Lean tool in digitalisation process that can further act as a catalyst for an I4.0 transformation without demonstration premises. The objective of the present work is to understand the critical requirements for a successful Lean transformation of an SME to the efficient I4.0 production platform using a manufacturing case study. Focusing I4.0 transformations on Lean concepts can simplify the transition from regional smart manufacturing concepts to larger modelling platforms such as big data and artificial intelligence. This research will significantly contribute to both manufacturing theory and practice with the establishment of a digital twin concept that is able to transform the equipment of SMEs to well organised and managed digital platforms.

2. Methodology

The research was carried out at medium size manufacturing company with 200 employees located in Galway, Ireland. The company manufactures fasteners primarily for the automotive market. It is high-volume, high-mix manufacturing with processes: machining, cold forming, cold heading (CH), second operations, heat treatment, electro plating, camera inspection and packing. The project is carried out at the primary operations CH department, with 17 employees, running a 24/5 shift pattern, focusing on 16 primary machines only, no secondary equipment associated with the CH department will be included in the project. The 16 primary machines all function in the same way, feeding raw material, in the form of wire, in through a wire drawer, where the wire is cut to the required length and then the blank wire pieces are shaped into a fastener using a ram to force a punch into a preformed die. Each machine follows a set production schedule of work orders of various quantities and product types. Run rates can vary between 130 and 320 parts per minute, and weekly production is in the region of 8 million pieces. Adherence to the schedule is dependent on each work order being completed on time to allow the next work order to start. The department have a core team who meet each day to review production activities, supervisor, quality engineer, manufacturing engineer, team lead and planner. OEE is a KPI used in the daily meetings and as such, was chosen as the Lean concept for digitisation. Preparing OEE data for all 16 machines is time-consuming and once complete, a digital VM system will add valuable data for the morning meetings, readily available each day.

2.1 Implementation model

This project applied the PDCA (Plan, Do, Check, Act) methodology which is a cycle of a continuous loop of planning, checking and acting. DMADV (Define, Measure, Analyse, Design, Validate) has not been considered here, as it is mostly focused on the design and development of new products or services which do not exist (Trubetskaya and Muellers, 2021). In the present work, PDCA methodology is preferred over DMAIC (Define, Measure, Analyse, Improve, Control) due to simplicity and potential to solve many problems at every level of the organisation using daily reporting (Eaidgah *et al.*, 2016). Both PDCA and DMAIC methodologies aim to improve processes within organisations, but each methodology focuses on different aspects of process improvement. PDCA is focused on measuring performance to identify problems and take corrective action as a comprehensive approach by focusing on the overall process. DMAIC's main goal is measuring performance as well as analysing data from various sources to find the root causes of problems to prevent them or fix them effectively by focusing on specific areas and monitoring results (Henrique, 2018). Building the PDCA cycle into the digital twin system, particularly the checking and acting mindset, helps VM platform to be more effective through continuous improvement.

To the knowledge of authors, this is the first work that investigates the integration of PDCA methodology into digital twin concept. Digitisation is not restricted to purely Lean tools, but it can appear as a starting point to begin a transformation with pre-defined parameters (Sartal *et al.*, 2022). In this work, digitisation includes the define and measure elements of DMAIC methodology, so that the continuous improvement teams start at the analysis phase. The control phase of digitisation includes trending data that is typically collected over long period of time to be able to monitor KPIs, and to create sustainability within a process. This allows not only the process to mature but also the control systems.

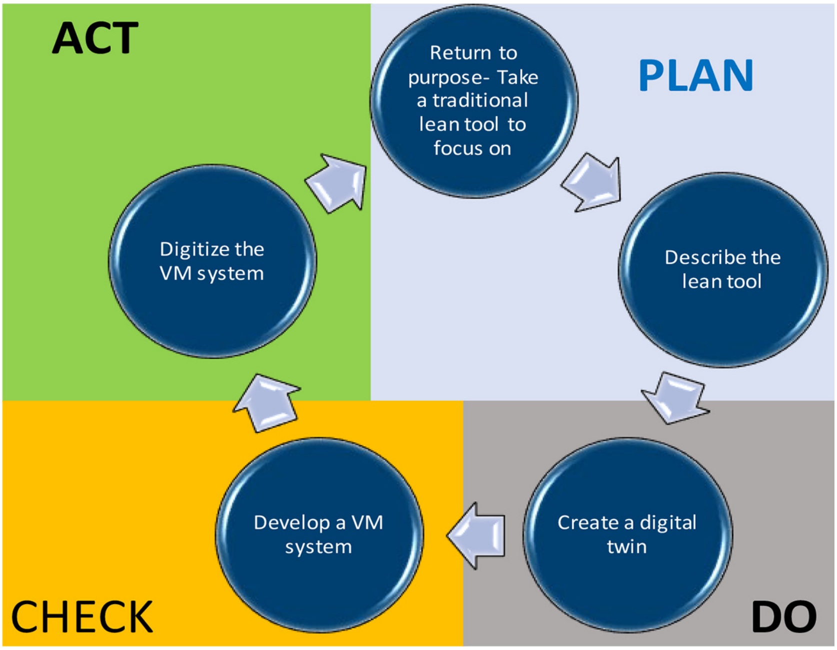
Thus, when digital twins of maturity level higher than 3 will be considered, it will be of interest to integrate DMAIC methodology (D'Orazio *et al.*, 2020).

The rationale for using PDCA in implementing the model was due to the iterative nature of the PDCA cycle (Isniah *et al.*, 2020). The proposed implementation model will include the creation of a digital twin of each machine. Creating a digital twin requires specialised technical knowledge. To assemble the project team, selection was based on individuals' technical knowledge and skills to solve problems, as well as members who use and work with OEE in the department each day, and the team selection was agreed with management. Communication, as always, in a project is key and weekly meetings were held to update all stakeholders on progress.

The model proposes to take the traditional Lean tool OEE and digitally transform it in the context of I4.0. Identifying and describing the Lean concept forms the Plan phase of the PDCA cycle, creating the digital twin forms the Do phase, developing the VM system forms the Check phase and digitising the VM system forms the Act phase (see Figure 1). The concept of digitisation is a key development brought about by I4.0. By demonstrating the digitisation of both OEE and the VM system, the organisations' goal of developing an I4.0 transformation will be satisfied.

2.2 Return to purpose

OEE is a best practice metric that identifies the percentage of planned production time that is truly productive. OEE is made up of three elements, Availability (A), Performance (P) and Quality (Q). Equation (1) is used to calculate OEE, and the result is expressed as a percentage (Sohal *et al.*, 2010):



Source: Author's own creation

Figure 1. Implementation model integrated with PDCA cycle

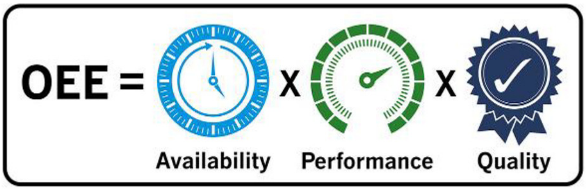
$$\text{OEE} = \text{A x P x Q} \quad (1)$$

Each element of OEE was listed and defined within the OEE calculations, see Figure 2. Availability is the percentage of time a machine is running for during the available time. Performance is the percentage of parts produced versus the target production. Quality is the percentage of good parts versus the total parts produced.

2.3 Developing the digital twin

A digital twin in the case of this project means describing the CH machines in terms of OEE in a digital manner. The process of creating a digital twin required the OEE elements to be captured at the machine and described in terms of the machine status, production pieces and scrap product and then used to calculate the OEE value. Table 1 formed the basis of the digital twin structure, whereby OEE elements were digitally represented at the machine by a status code. The status of each machine was captured using a programmable logic controller (PLC), which are commonly used in industry. The PLC programme monitored the machine signals and reported a status code that depends on the state of the logic within the PLC programme. The status codes are a digital representation of all required elements to calculate OEE as per equation (1) and Figure 2. A code was created for each status, and linked to the OEE descriptors (see Table 1). A Status code 0 was added to monitor the communication status of the system, and alert users if there was an interruption to the data.

The availability element of OEE is known to require the recording of how much time the machine spends in run mode producing parts. In this instance, the PLC programme captures when the machine is in run mode producing parts and indicates a Status 1 signal. This is logged in the data base for as long as the machine status remains at Status 1, thus giving a time for the running time element. Status codes 2–8 are defined as downtime. The preference



	Calculation	ONE SHIFT			
Available time	Shift time - Unavailble time	Available time			Scheduled Unavailable
Availability (%)	Running time / Available time	Running time		Down time	
Performance (%)	Total units produced / Actual run time / Ideal cycle time	Production @ rated speed	Speed losses		
Quality (%)	Total - Scrap / Total	Good Production	Scrap		
OEE	A x P x Q	OEE %	Lost capacity (%)		

Source: Author's own creation

Figure 2. OEE elements and calculations

Table 1.
Digital transformation of OEE elements into status codes

Status code	Status description	OEE discriptor	OEE element
0	No comms	System quality check	
1	Machine in run mode	Running time	
2	Setup/CO		
3	Wire-up		
4	Planned maintenance		
5	Unplanned maintenance	Downtime	Availability
6	Problem solving		
7	Too change		
8	Thread roller		
9	Not scheduled	Scheduled unavailability	
10	Total machine cycles	Total units produced	Performance
11	Target run rate	Ideal cycle time	
12	Scrap	Scrap	Quality

Source: Authors' own creation

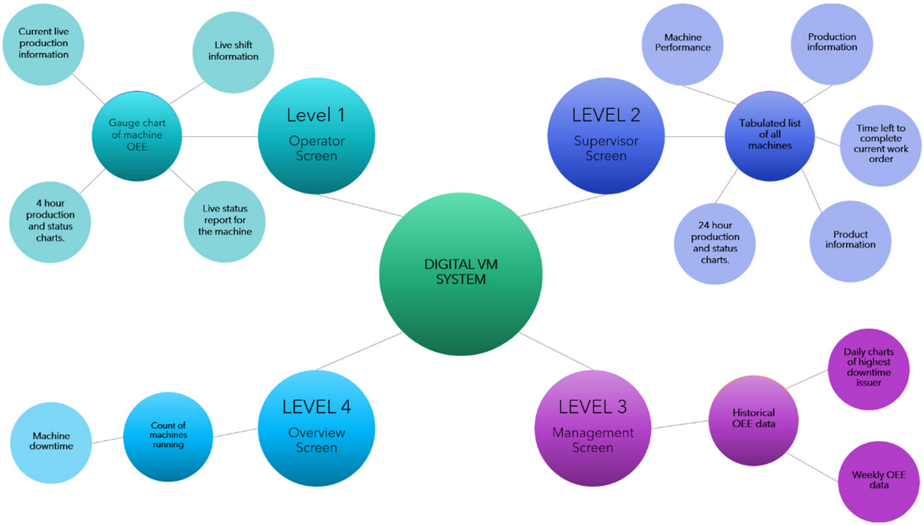
was to automate data collection, but this is not always possible so some manual interaction from the operator was necessary to capture downtime reason codes, and this was accomplished using a human machine interface (HMI) connected to the PLC, whereby when prompted, the operator enters data by pressing the appropriate downtime reason button on the touchscreen HMI (see Figure A-1 in Appendix A). A database was set up to store the data as it was captured by the PLC and HMI.

Manual inputs can be missed or forgotten, and to overcome this a Poke Yoke was introduced. Once the machine stops making parts, the PLC programme recognises this new status as downtime, regardless of operator interaction. The machine returns to Status 1 once the operator has resolved the issue that caused the stoppage and restarts the machine so that it is once again running and making parts. At this point, the HMI will prompt the operator to enter a reason for the downtime. The HMI will remain on this screen until a code is entered, so the operator cannot move to a new screen until he chooses a reason for the downtime. This method proved effective in accurately capturing reason codes for down time. The remaining status codes, total machine cycles Status 10, target run rates Status 11 and Scrap Status 12, provided values for Performance and Quality elements in Figure 2. The PLC and HMI continuously logged data to a database, providing automated OEE data, which was easily accessible to the core team, and created a more efficient means of reporting OEE for 16 machines each day.

2.4 Development of a VM system

Capturing data in terms of I4.0 is carried out with the purpose of providing a single source of truth and empowering an organisation to make data-based decisions. However, capturing data is wasteful if it is not utilised. The digitised OEE data needed to be integrated into the cadence of the department's daily activities if it was going to be utilised and make the OEE reviews more efficient. The operators were trained for two weeks on how to use the new data entry system, whereas the core team was learning about the new OEE database.

VM requires the sharing of information on standards and can warn about abnormalities and stop the manufacturing process if the abnormalities are identified. A series of OEE charts were developed from the new database, printed and displayed on KPI boards in the department. The benefits of displaying the OEE information are ease of understanding, as



Source: Author's own creation

Figure 3. VM system design using four levels of visual display

visual information is more easily understood, and speed of communication; the new data was readily available in a format to automatically generate OEE calculations. The daily meetings were changed from a system of reviewing data to action-based meetings, whereby abnormal conditions required an action which would be reviewed the following day. As part of the organisations' continuous improvement programme, projects such as single-minute exchange of dies (SMED), total preventative Maintenance and changeover training were implemented quickly after the start of the new daily review meetings, that will not be discussed as part of this research. The focus for the team then shifted to digitising the VM system.

2.5 Digitisation of the visual management system

Providing the right information to the right people at the right time is a key element of digitisation in I4.0. The digital VM system was designed using four levels of information, based on end user requirements (see Figure 3). Level 1 displays OEE information at each machine for the operator (see Figure B-1 in Appendix B).

Level 2 provides summary information for all machines to the core team. This allows the team to monitor all machine statuses and performance in one place (see Figure B-2 in Appendix B).

Level 3 provides historical data for management review. OEE for each machine for the previous 24 h is provided as well as each element of OEE, A, P and Q. In addition, Level 3 also provides a visual of the downtime for each machine and indicates which downtime reason contributed most to the downtime (see Figure B-3 in Appendix B).

Finally, Level 4 provides high level departmental information of each machine status. The status of all 16 machines will be shown, to allow anyone walking through the department to know how many machines are running and how many are down. If a machine is not running the reason is displayed and the length of time it has been in this status is also displayed (see Figure B-4 in Appendix B).

Digitisation of the VM system was carried out using the data analytics and visualisation software Qlik®. For Level 1, a 22-inch display was mounted at each machine to visualise OEE data. Apps were created within Qlik® for the supervisor and management displays: Levels 2, 3 and 4. Level 4 information was displayed on two 60-inch TV screens mounted on walls each side of the department. The purpose of Level 4 is to alert the supervisor and team lead when machine stoppages occur, and concurrently to provide the information on how long each machine was out of service. The supervisors and team leads can then react and get the machines running again, or allocate resources required to resolve the issue.

3. Results

3.1 Establishment of a digital twin

The fundamental aim of the research was to establish a digital twin of each machine. A digital twin of each machine is presented, providing a visual representation of the behaviour of each machine in terms of OEE, that is, how much time it is in run mode producing good product versus how much time it is not running and therefore not producing product (see Figure 4).

Each machine is represented digitally in two ways for live visualisation of machine behaviour. On the top graph in Figure 4, the quantity of pieces which are manufactured each hour are blue marked. The red section on top or bottom of each bar indicates the delta

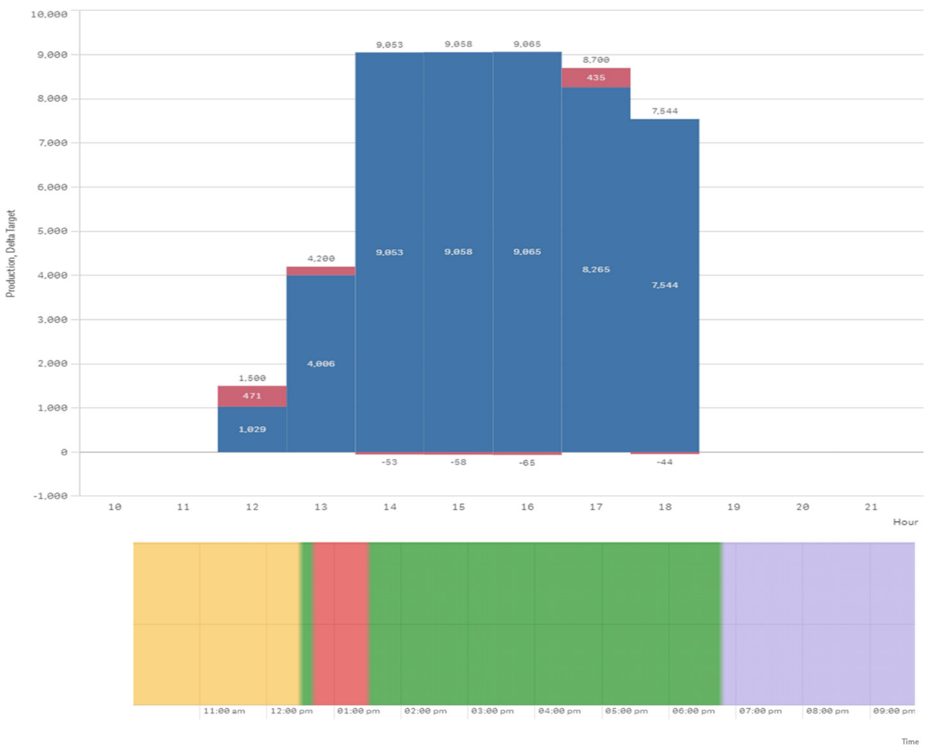


Figure 4.
Digital twin showing hourly production and colour coded machine status indicators

Source: Author's own creation

between actual pieces produced versus the ideal target quantity. The bottom graph in Figure 4, shows a ticker tape type visualisation of the machine. The colour-coded chart allows the user to quickly determine the machine behaviour over time, with each colour representing a machine status. When the machine is in production and producing parts, plotted points in time are green marked. In instances where production is stopped, the chart colour changes to red. The purple colour marking is used for unscheduled, and the yellow identification is used to illustrate changeovers. A supervisor, during chart reviews, wants to see large sections of green. Large red areas are used to indicate extended downtime, while frequent small red lines represent intermittent recurring issues.

The digital twin illustrates a quick visualisation of the machine performance over time, bringing together sensing inputs, computing power, always on connectivity and data analytics, all of which work on an I4.0 platform to develop smart manufacturing. An individual chart for any machine can be readily produced from the data to indicate which element of OEE contributes most to the OEE losses, (see Appendix C, Figure C-1). Users can then quickly identify, using the digital twin, which of the six big losses typically associated with OEE elements (see Appendix C, Figure C-2), are the main contributors to downtime, and implement projects as part of the continuous improvement programme.

Two scenarios were observed, and further discussed, which may not have been otherwise observed if the digital twin was not in place. Firstly, erratic production performance, whereby the actual pieces produced may show a small delta to the target, but the total production (actual pieces produced plus the delta), resembles a staircase, (see Appendix D, Figure D-1). This behaviour indicates unplanned interruptions at the machine.

Secondly, consistent performance was observed whereby, both the pieces produced and a small delta to the target were similar over a period of hours, indicating that the target production value was correct. Conversely on some equipment, consistent pieces per hour were observed with a large delta to the target over a period of hours (see Appendix D, Figure D-2). Further analysis revealed that the target pieces in place was not realistic for the part being produced due to the difficulties associated with processing the material in use, resulting in a consistent low performance, giving a false low OEE. Once corrected true OEE illustration was produced, a more realistic indication of issues affecting OEE performance appeared.

Both charts, shown together, allows the user to see which down time reason was responsible for the reduction in manufacturing performance. The charts were designed as part of Level 2 for the core team. A team meeting identified that using the charts over a shorter period of 4 h and visualised on the Level 1 operator screen, would allow the operator of each shift to review how the machine had performed on the previous shift.

3.2 Developing and digitising the VM system

The results of this work indicated that the digital VM system had an overall positive impact on the departmental OEE in a relatively short period of time. Initially, OEE charts were displayed on departmental KPI boards as part of the VM system, however, results were not consistent indicating that there were additional factors contributing to low OEE.

Once the digital VM system was introduced an increase in the departmental OEE was observed. The introduction of the digital VM system required the core team to review instances of high OEE loses each day and to act. This involved going to the operator of the machines and discussing the issues, before introducing improvements. Of the 16 machines in the department, 88% showed a positive improvement in OEE performance, as shown in Figure 5. The remaining two machines which showed a 3.1% and 6.5% decrease in OEE performance, had an adjustment made to the target performance values based on the digital

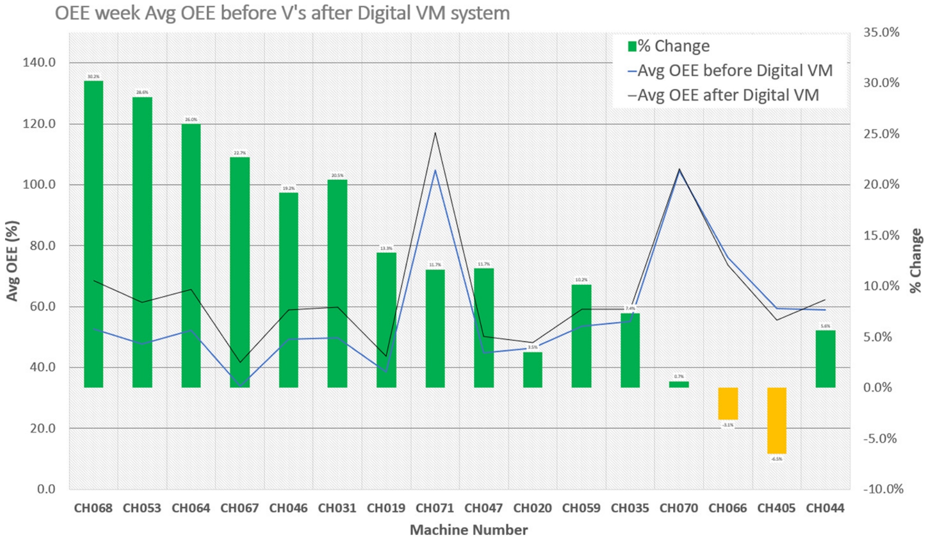


Figure 5.
OEE % improvement by machine, showing 14 out of 16 machines with a positive improvement

Source: Author's own creation

VM data. Analysis of the data for these two machines had shown that the performance element of OEE was always greater than 100%, indicating that the target production value was under rated. The target values were corrected to give a more reflective OEE result, which resulted in the OEE decrease.

One of the difficulties with any transformation programme is related to sustainability. Sustainability barriers for OEE systems are related to difficulties in generating, analysing, and displaying results which can cause a loss of momentum and engagement. The digital twin concept meant that OEE data was always readily available to the core team. Furthermore, the digitisation of the VM system resulted in all the daily meeting spent discussing results and actions rather than data integrity. The digital VM system became integrated in the cadence of the department daily activities right after positive results were observed. As such the digital VM system becomes self-sustaining, as the department core team become reliant on the information and found new ways to utilise and analyse the data.

A key objective of the research was to enhance the performance of OEE within the CH department. Enhancing the performance of any Lean tool is reliant on a stable process, which is critical to sustainability. The daily production meetings and improvement actions resulted in the department OEE becoming more consistent. Overall, a 10% increase in the department OEE was observed since the introduction of the digital VM system, contributing significantly to the productivity of the department, and more importantly the OEE increase has been sustained over a long period of time (see Figure J–1, Appendix J).

3.3 I4.0 and digitisation

Development of I4.0 within the organisation will be a determining factor for the success of the research. While OEE results have been excellent and sustained over a long period, the model proposes to develop I4.0 by focusing on digitising traditional Lean tools. To demonstrate I4.0 there must be evidence of innovation and digitisation. Furthermore, there must be evidence of a synergy between I4.0 and Lean.

As mentioned in Section 2.5, data analysis from the digital VM system indicated that changeovers were having a significant impact on lost production time. An SMED project was ongoing within the CH department to reduce lost time to changeovers. In spite of the project successfully, identifying and segregating internal and external factors required for a changeover, produced an ideal target changeover time, and setting up visual aids within the department, changeovers continued to account for 20% of the downtime for some machines. SMED was proposed for digitisation as per the implementation model used in the case study. As part of the digital twin development an HMI was used at each machine. The internal factors required for the changeover process were digitally displayed on the HMI as a series of steps (see Figure E-1 in Appendix E). The operators were required to select each step in sequence so that the designed changeover process was followed. In addition, for longer changeovers it provided a record for operators if the changeover crossed shifts, which steps were completed and what stage the changeover was at. In addition, a video of each step is available to view on the HMI, as a reference of how to complete the step.

Process observations revealed that the internal elements of the changeover were followed and met the designed time. However, by analysing the raw data generated from the machine it was observed that some machines were stopped for up to 40 min before the changeover started. This was valuable information provided by the digital VM system to enhance SMED. Two further improvements were added to the HMI. A visual alert appears on the HMI 2 h prior to the work order completion, to prompt the operator to start preparing the external elements required for the changeover. Once the target work order quantity is reached the machine automatically stops, preventing over production of pieces. Data analysis showed that lost time due to changeovers reduced from 20% to 12% of the total downtime after integration of SMED to the digital VM system, see Figure 6. Additional improvement projects were identified from the digital VM data and decreases in downtime for tool change, problem solving and thread roller were also achieved.

The OEE and SMED digitisations were carried out within the CH department. An organisations I4.0 transformation cannot be demonstrated by limiting it to one department. As part of the CH digitisation, knowledge and skills have been developed within the organisation. Over the course of 12 months, the organisation has become more efficient at identifying and affecting digital transformations. A replicate of the CH digital VM system has since been introduced at the cold forming department. The team have identified additional equipment across the value stream that are judged to be ready for connectivity increasing both the vertical and horizontal integration of equipment in the organisation (see Figure F-1 in Appendix F). A programme is in place in the screw machine department to add PLCs and HMIs to older mechanical equipment that will generate OEE data (see Figure F-2 in Appendix F). The pace of digitisation has increased, 16 machines had digital twins created in 2021, by the end of 2022 a further 31 pieces of equipment will have digital twins created.

An additional objective of the research was to demonstrate that focusing I4.0 transitions on Lean concepts will simplify the transition from regional smart manufacturing concepts to larger modelling platforms such as big data and artificial intelligence. Regional smart manufacturing improvement has been successfully implemented in terms of vertical integration, digital twins and the introduction of digital VM systems. All data that is generated from digitisation is stored in a cloud-based data lake. The implementation model has also been applied to the organisation's transactional processes, focusing on the enterprise resource planning (ERP) system. A complete set of process maps have been generated for all transaction processes (see Figure G-1 in Appendix G). The maps have identified dysfunctionality across the processes and made waste visible within the system. By mapping the information flow, opportunities for automation have been identified and

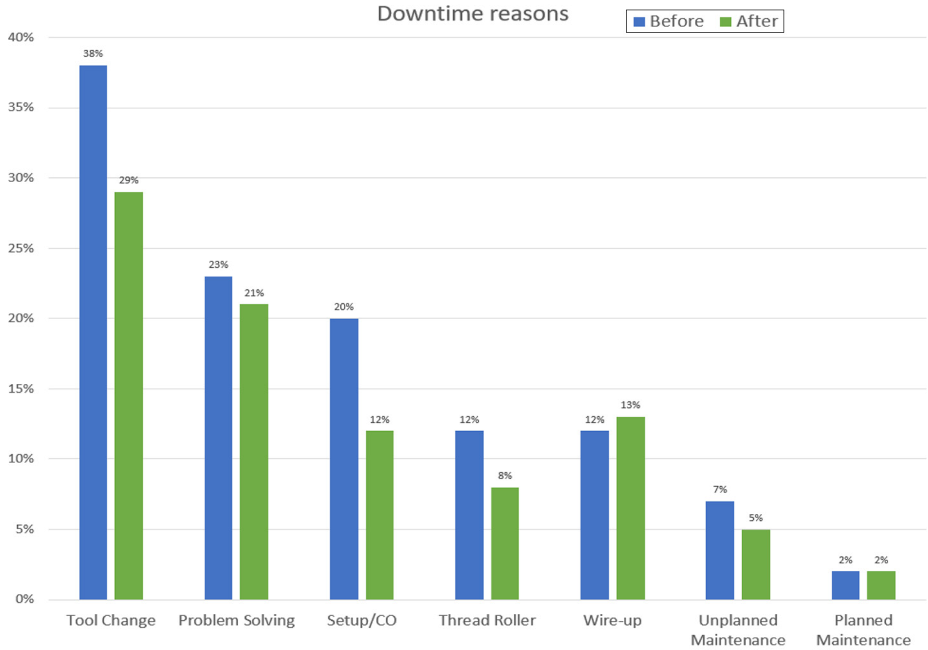


Figure 6.
Downtime issue as a percentage of total downtime before Vs after digitisation

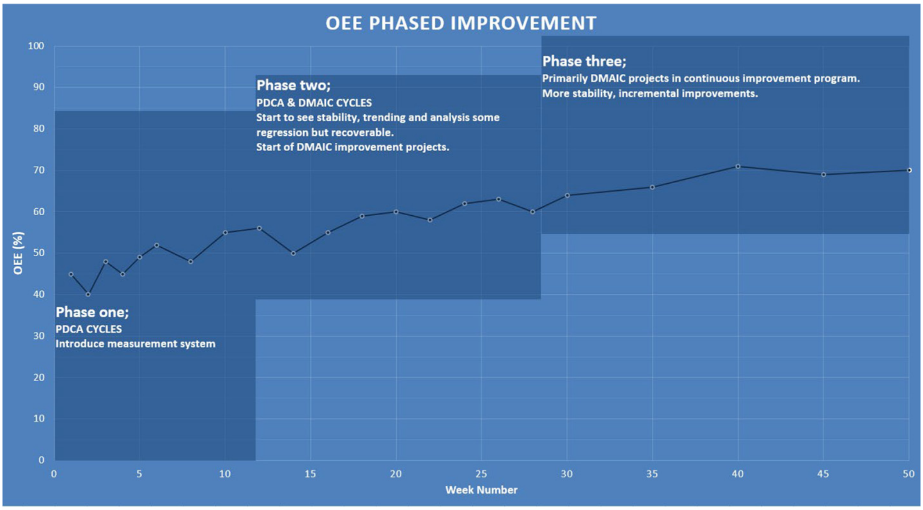
Source: Author's own creation

completed. Furthermore, a digital map of all work orders across the value stream is in the DO phase of the model, whereby a digital twin of the work in progress will be generated (see Figure G-2 in Appendix G). This will allow analysis of product flow across the value stream.

4. Discussion

The objective of the research was to create an implementation model based on a traditional Lean tool which would provide SMEs with a practical approach to initiating I4.0 and digital transformations. Furthermore, the article research goal was to show that focusing I4.0 transformations on Lean tools would simplify the transition from smart concepts to larger modelling platforms. Achieving the requirements of maturity models is difficult for SMEs (Mittal *et al.*, 2019), and suggests that a Level 0 is required to allow SMEs to map basic business operations, as shown in the I4.0 transformation road map (see Figure H-1 in Appendix H).

To demonstrate the effectiveness of focusing I4.0 transformations on traditional Lean tools, a case study was carried out at a manufacturing department of the SME. A phased improvement was observed within the manufacturing department, whereby firstly stability was introduced which allowed continuous improvement projects to run and generate further incremental improvement (see Figure 7). Prior to digitisation the departmental OEE results were inconsistent, as it was identified as Phase 1. The implementation barriers result in inconsistencies which are typical to observe in traditional VM systems (Kurpjuweit *et al.*, 2019). The current research has found that a digital VM system is not as susceptible to some of the barriers previously identified, such as lack of resources, complexity of underlying processes, organisational culture and resistance by shop floor personnel to changes in their daily routine. The proposed model requires the system to be fully mapped prior to creating the digital twin,



Source: Author's own creation

Figure 7. Phased OEE improvement observed over 50 weeks

thus simplifying a complex process. The digital twin automatically records and stores data continuously, therefore there is no requirement for a resource to gather data, and the visualisations of the data in terms of OEE charts removes the requirements for resources to generate charts each day. The segregation of the digital VM system into four levels delivers visual information to different users and becomes part of the manufacturing process, integrating itself into the culture of the organisation, where digital visualisations become the norm.

VM is best understood as a fitness factor (Tezel and Aziz, 2017), rather than a silver bullet to resolve issues within a process or system. A digital VM system will not deliver sustained performance improvements in and of itself, but rather provides real-time data, making the detection of waste or abnormalities more efficient as suggested by previous research (Mrugalska and Wyrwicka, 2017). This is one of the important findings of the research, that integrating Lean into a digital environment creates the required synergy between Lean and I4.0, thus increasing the chances of a successful I4.0 transformation and enhancing Lean tools. Moreover, the updating of VSMs is more time-consuming and resource heavy in larger enterprises than at SMEs (Pagliosa, 2021). When OEE is considered not as a part of metrics, I4.0 transformations using various Lean tools could increase the chances of successful digitalisation in both SME and large enterprises.

In the case study, the lowest performing machine in terms of OEE was identified and the factors contributing to the losses were visualised. This allowed continuous improvement projects to be identified in a targeted way. The departmental core team ran multiple projects based on the digital VM system data and achieved an incremental improvement in the departments' OEE. Results became more consistent as seen in Phase 2 (see Figure 7).

While the case study was used to develop the model, other digitisation use cases were quickly identified and implemented. The HMI used by the operators to input data was also used to digitally display the changeover steps with demonstration videos available (see Figure E-1 in Appendix E). This enhanced the departments' SMED programme and reduced the lost production time associated with changeovers from 20% to 12%. An automatic shutdown of the machine was introduced when the work order target quantity was reached, removing overproduction as an issue within the department. This had the effect of increasing the efficiency of the production schedule. Combined, the use cases have seen the department shift to Phase 3 of Figure 7, where consistent OEE results are reported over extended periods (see Figure I–1, Appendix I).

As the departmental OEE improvement was sustained over a long period of time, the finance team was able to directly attribute a financial improvement to the organisations profit reports. Recovered hours versus paid hours forms a high level KPI for the organisation, and a significant increase was recorded for the CH department. OEE improvement within the CH department was costed at €156,000, contributing significantly to the organisations' cost-saving programme, and timely in the current economic climate where price increase has become the norm.

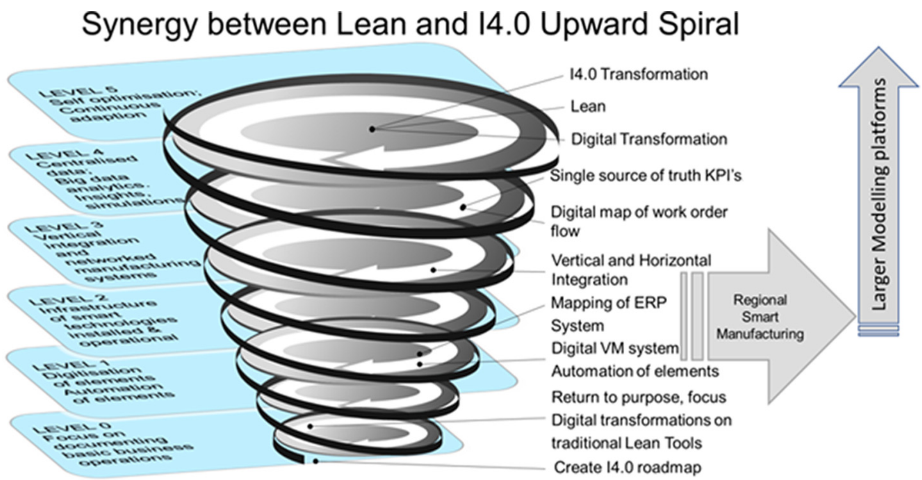
Digitising the OEE VM system has acted as a catalyst for the digitisation of other Lean tools and progressed the I4.0 transformation in the organisation. While the research was carried out in an SME, the results are applicable to organisations of all sizes. Lean tools have been previously shown to be effective in removing waste and adding value across a wide range of industries. As the model presented is centred around a Lean tool, it can be used as a practical implementation model in any organisation where Lean is in use or can be introduced.

Simplification of the transition from regional smart manufacturing to larger modelling platforms is defined as one of the research goals. In a Lean environment three sets of flow can be identified, material, information and cash (Eaidgah *et al.*, 2016). A smart manufacturing process has been developed at the CH department, in the form of digital twins, where the case study was carried out. This is representative of material flow in the Lean environment. The mapping of the organisations ERP system and the digitisation of work order flow is currently underway and can be seen as the information flow aspect of the Lean environment. This will represent the digitisation of two of the main sets of flow. Once complete there will be centralised available data and combined with the existing cash flow system represents the creation of digital big data for the organisation. Larger modelling platforms can then be applied in the form of big data analytics and AI.

The pace of vertical integration within the organisation has increased, with a digital twin of a further 31 machines in progress. This is described as an upward spiral, created by the synergy between Lean and I4.0 (see Figure 8), whereby a catalyst project based on a traditional Lean tool can generate multiple opportunities for further digitisation of Lean tools and systems.

In a spiral model, the radial coordinate represents progress in digitalisation and transition from regional smart manufacturing to larger modelling platforms, whereas the angular coordinate represents progress in completion of the model maturity (Boehm, 1988). Figure 8 illustrates a spiral development in I4.0 and digital transformation aiming to decrease risks and to guide stakeholders using a cyclic approach with anchor point milestones (Hantos, 2000). By using this spiral model, the maturity level of the enterprise can be estimated in a short time to identify the most suitable rules for the planning of short-term realistic milestones in each spiral cycle (Sanchez-Crespo, 2006). Critical to the success of the I4.0 upward spiral development was identifying and applying the level 0. Successful digitalisation and I4.0 transformation in SME requires continuous improvement and structural deviation into detailed maturity levels, whereas level 0 plays a role of a baseline in the entire spiral model development (Ke *et al.*, 2021).

Data mining, predictive manufacturing and big data analytics are all integral to the final development of an I4.0 transformation. Focusing on traditional Lean tools has allowed to generate rich sources of valuable data, with a specified purpose, avoiding the pitfalls experienced by SMEs when attempting digital transformations, whereby a vast array of software, no integration and over production of data leads to the failure of the transformational



Source: Author's own creation

Figure 8. Upward spiral created from Synergy between Lean and I4.0

process. As the speed of vertical and horizontal integration has increased dramatically over the course of 12 months, it was observed within the organisation and globally that the network connectivity and infrastructure available to support the new connections, data transfer and visualisations has not kept pace (see Figure J-1 in Appendix J). Traditional IT structures and processes will need significant improvements if they are to facilitate a true I4.0 transformation. Indeed, further research is essential in this area, to allow organisations to prepare for the big data analytics required to move smart technologies from data generation vehicles to predictive manufacturing. If the I4.0 journey that has begun is to be fully realised then the infrastructure and process of visualisation, data mining and analytics must outpace current vertical and horizontal integration and stay ahead of future technological innovations, within the organisation. It is only then that the benefits promised by the I4.0 revolution can have a real transformational impact on modern manufacturing in the same way as Lean had for Toyota.

While AI has not been implemented yet, the data lake and flow of data to the data lake means the organisation is becoming AI ready and can start the process of identifying the key skillset required to facilitate the next stage of the I4.0 transformation. Reflecting on the previous 12 months from the generation of an I4.0 roadmap, linking it to the organisations operational excellence journey and digitising the OEE VM system, all of which have acted as a catalyst for change in digitisation, and prepared a platform for the organisations' I4.0 transformation.

5. Conclusion

The novelty of this work relies on the establishment of synergy between digitalisation and Lean tools through introduction of maturity level 0. The PDCA methodology provided novel opportunities for each Lean tool to digitise another Lean tool and thus, establish a positive synergy and momentum when each digital element comes online. The results showed that the I4.0 transformation was successful due to the clearly defined purpose of each data point gathered and replicated in other projects across the value stream. This work presented a model of the digital twin at level 3 maturity, with vertical integration of 16 primary manufacturing equipment, that provides live continuous data to the cloud. In spite of a great success to report efficiently and timely OEE data to the core team, the digital twin model can be further developed to level 4 maturity using centralised big data collection that can be used in both SMEs and large enterprises. This work serves as an inspiration to perform more investigations on the connectivity support and conversion of stored data into visualisations and predictive analytics using a spiral I4.0 and Lean synergy development map.

References

Baskin, K. (2022), "Study examines how machine learning boosts manufacturing", MIT news, on campus and around the world, 1 March, Issue March 1, 2022, p. 1.

Bateman, N., Philp, L. and Warrender, H. (2016), "Visual management and shop floor teams – development, implementation and use", *International Journal of Production Research*, Vol. 54 No. 24, pp. 7345-7358.

Bititci, U., Cocca, P. and Ates, A. (2016), "Impact of visual performance management systems on the performance management practices of organisations", *International Journal of Production Research*, Vol. 54 No. 6, pp. 1571-1593.

Boehm, B. (1988), "A spiral model of software development and enhancement", *Computer*, Vol. 21 No. 5, pp. 61-72.

Borkar, S. and Rai, A. (2019), "A review paper on visual factory", *International Research Journal of Engineering and Technology*, Vol. 6 No. 7, pp. 1314-1316.

Buer, S.-V., Strandhagen, J.O. and Chan, F.T. (2018), "The link between industry 4.0 and lean manufacturing: mapping current research and establishing a research agenda", *International Journal of Production Research*, Vol. 56 No. 8, pp. 2924-2940.

D'Orazio, L., Messina, R. and Schiraldi, M.M. (2020), "Industry 4.0 and world class manufacturing integration: 100 technologies for a WCM-I4.0 matrix", *Applied Sciences*, Vol. 10 No. 14, pp. 1-24.

D'Silva, V. and Lawler, B. (2022), "What makes a company successful at using AI?", *Harvard Business Review*, Issue 28 February, 2022.

Eaidgah, Y., Maki, A.A., Kurczewski, K. and Abdekhodaee, A. (2016), "Visual management, performance management and continuous improvement lean manufacturing approach", *International Journal of Lean Six Sigma*, Vol. 7 No. 2, pp. 187-210.

Hantos, P. (2000), "From spiral to anchored processes: a wild ride in lifecycle architecting", *Proceedings, USC-SEI Spiral Experience Workshop*, *Los Angeles, CA*.

Henrique, D. (2018), "Sustaining lean thinking in healthcare: case studies", Sao Carlos: PhD thesis. Federal University of São Carlos.

Hofmann, E. and Rusch, M. (2017), "Industry 4.0 and the current status as well as future prospects on logistics", *Computers in Industry*, Vol. 89 No. 1, pp. 23-34.

Isniah, S., Purba, H.H. and Debora, F. (2020), "Plan do check action (PDCA) method: literature review and research issues", *Jurnal Sistem Dan Manajemen Industri*, Vol. 4 No. 1, pp. 72-81.

Jaca, C., Viles, E., Jurburg, D. and Tanco, M. (2014), "Do companies with greater deployment of participation systems use visual management more extensively? An exploratory study", *International Journal of Production Research*, Vol. 52 No. 6, pp. 1755-1770.

Ke, Y., Qui, Y. and Yang, Z. (2021), "Study on the maturity of construction technology in China", *IOP Conference Series: Earth and Environmental Science*, *Xiamen*.

Kolberg, D. and Zuhlke, D. (2015), "Lean automation enabled by industry 4.0 technologies", *IFAC-PapersOnLine*, Vol. 48 No. 3, pp. 1870-1875.

Kurpjuweit, S., Reinerth, D., Schmidt, C.G. and Wagner, S.M. (2019), "Implementing visual management for continuous improvement: barriers, success factors and best practices", *International Journal of Production Research*, Vol. 57 No. 17, pp. 5574-5588.

Mittal, S., Khan, M.A., Romero, D. and Wuest, T. (2019), "Smart manufacturing: characteristics, technologies and enabling factors", *Journal of Engineering Manufacturing*, Vol. 233 No. 5, pp. 1342-1361.

Mrugalska, B. and Wyrwicka, M. (2017), "Towards lean production in industry 4.0", *Procedia Engineering*, Vol. 182, pp. 466-473.

Murata, K. and Katayama, H. (2016), "Performance evaluation of a visual management system for effective case transfer", *International Journal of Production Research*, Vol. 54 No. 10, pp. 2907-2921.

Ohno, T. (1988), *Toyota Production System, beyond Large Scale Produciton*, 1 ed., CRC Press, FL.

Pagliosa, M., Tortorella, G. and Espindola Ferreira, J.C. (2021), "Industry 4.0 and lean manufacturing, a systematic review and future research directions", *Journal of Manufacturing Technology Management*, Vol. 32 No. 3, pp. 543-569.

Rossini, M., Cifone, F.D., Kassem, B., Costa, F. and Portioli-Staudacher, A. (2021), "Being lean: how to shape digital transformation in the manufacturing sector", *Journal of Manufacturing Technology Management*, Vol. 32 No. 9, pp. 239-259.

Sanchez-Crespo, L.E. (2006), "Building a maturity security model based on ISO 17799", *The International Conference on Computational Sciences and Its Applications*, *Glasgow*.

Sartal, A., Llach, J. and Leon-Mateos, F. (2022), "Do technologies really affect that much? Exploring the potential of several industry 4.0 technologies in today's lean manufacturing shop floors", *Operational Research*, Vol. 22 No. 5, pp. 6075-6106.

Sohal, A., Olhager, J.O., Neill, P. and Prajogo, D. (2010), *Implementing OEE – Issues and Challenges*, APMS, Cernobbio, Como.

Tezel, A. and Aziz, Z. (2017), "Visual management in highways construction and maintenance in England", *Engineering, Construction and Architectural Management*, Vol. 24 No. 3, pp. 486-513.

Tezel, A., Koskela, L. and Tzortzopoulos, P. (2016), "Visual management in production management: a literature synthesis", *Journal of Manufacturing Technology Management*, Vol. 27 No. 6, pp. 766-799.

Torres, D., Pimentel, C. and Duarte, S. (2020), "Shop floor management systems in the context of smart manufacturing: a case study", *International Journal of Lean Six Sigma*, Vol. 11 No. 5, pp. 837-862.

Tortorella, G.L. and Fettermann, D. (2018), "Implementation of industry 4.0 and lean production in Brazilian manufacturing companies", *International Journal of Production Research*, Vol. 56 No. 8, pp. 2975-2987.

Trubetskaya, A. and Muellers, H. (2021), "Transforming a global human resource delivery operating model using lean six sigma", *International Journal of Business and Management*, Vol. 13, pp. 1-16.

Van Assen, M. and de Mast, J. (2019), "Visual performance management as a fitness factor for lean", *International Journal of Production Research*, Vol. 57 No. 1, pp. 285-297.

Zhong, R.Y., Xu, X., Klotz, E. and Newman, S.T. (2017), "Intelligent manufacturing in the context of industry 4.0: a review", *Engineering, Beijing*, Vol. 3 No. 5, pp. 616-630.

Supplementary material

The supplementary material for this article can be found online.

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