

Matching Digital Technologies with Lean Practices in Production

Robin von Haartman

Department of Industrial Management,
University of Gävle, Gävle, Sweden
Email: rhn@hig.se (*Corresponding Author*)

Jasna Prester

Faculty of Economics & Business,
University of Zagreb, Zagreb, Croatia

Lars Bengtsson

Department of Industrial Management,
University of Gävle, Gävle, Sweden

Camilla Niss

Department of Industrial Management,
University of Gävle, Gävle, Sweden

ABSTRACT

Lean production has been the most prominent method for improving operational performance in manufacturing companies. Recently, research has shifted to examining how digital technologies can make Lean more effective. The purpose of this paper is to explore which digital technologies used in production are associated with which internal Lean practices. The paper is based on a large-scale survey of manufacturing plants in Sweden and Croatia, and the data is analysed using correlation-, principal component- and regression analysis. Eight commonly used technologies in production were selected and linked to six internal dimensions of Lean. Statistically significant associations were found between around half of the digital technologies and the six dimensions of Lean. The overall conclusion is that the internal dimensions of Lean are highly intertwined with the usage of digital technologies in production. The paper thus offers insights for managers in Lean organisations that seek to implement digital technologies in production. The paper contributes to the digital Lean discussion by providing quantitative evidence on specific links between Digital technologies and specific Lean dimensions in manufacturing.

Keywords: *digital technologies in production, industry 4.0, lean manufacturing, lean production*

1. INTRODUCTION

Lean production has, in the last several decades, arguably been the most prominent method for improving operational performance in manufacturing companies (Marley and Ward 2013). Its aim is to reduce waste and non-value-added activities (Emiliani 2006) by adhering to certain principles. Lean production has been presented and conceptualised at different levels, such as guiding

principles, principles for guiding implementation, and the actual production practices (Cifone *et al.* 2021). One of the most prominent papers at the practices level is Shah and Ward (2007), who operationalised Lean along ten dimensions.

Lately Industry 4.0 (I 4.0), which is built on digital solutions and connected machines, has been making big inroads into academia and practice (Lu 2017; Moeuf *et al.*, 2020). Earlier papers emphasised the difference, or even conflict, between the two concepts (e.g., Hirsch-Kreinsen 2016), whereas most recent papers seem to see the concept as compatible or even synergistic (e.g., Rüttimann and Stöckli 2016; Buer *et al.* 2021; Cifone *et al.* 2021; Vinodh *et al.* 2021). The focus on Lean has recently shifted to examining how specific digital technologies can make Lean more effective (e.g., Rosin *et al.* 2020). One explanation for the seemingly synergistic relationship is that companies are adopting new technologies to reduce waste and thus make companies leaner (Rosin *et al.* 2020). However, there is a lack of empirical studies showing how and which digital technologies can enhance Lean production (Cifone *et al.* 2021), and a particular lack of quantitative studies. The quantitative studies that currently exists tend to be rather general (e.g., Rossini *et al.* 2019; von Haartman *et al.* 2021), showing that there is indeed a link between an overall level of digitalisation and an overall level of Lean. Other studies focus on the impact of specific technologies on a narrow definition of Lean (El Abbadi *et al.* 2018; Pekarčíková *et al.* 2019; Vinodh *et al.* 2020). Hence, there is a specific lack of research providing insight into how various technologies are associated with various Lean practices, using a broad, yet specific, definition of Lean. Knowledge resulting from such research could be used as a basis for strategical decisions on appropriate socio-

technical configurations in operational manufacturing practices.

Hence, the purpose of this paper to explore which of the commonly used digital technologies used in production are associated with which internal Lean practices. As noted by Cifone *et al.* (2021), it is important to understand these linkages; it is highly likely that some digital technologies are better at supporting Lean practices than others. For this paper, eight commonly used technologies in production were selected and linked to the six internal dimensions of Lean proposed by Shah and Ward (2007). The paper is thus limited to these particular technologies (**Table 1**), and also excludes Shah and Ward's (2007) external dimension of Lean, i.e. those linking the focal firm with customers and suppliers. Moreover, the empirical data is limited to two European countries: Croatia and Sweden. The paper relies on survey data collected in these countries during 2019. Nonlinear principal component, correlation and multiple regression analyses were employed for the statistical analysis.

1.1 Research Questions

As will be discussed in section 2, literature review, there are several studies reporting a synergistic relationship between Lean and digital technologies on an overall level, and some even with regard to the six dimensions of Lean included in this paper. However, there is still not sufficient literature to formulate hypotheses for each combination of the internal Lean dimension as defined by Shah and Ward (2007) and specific digital technology. This paper will thus adopt a more explorative approach and explore six research questions:

- RQ1: Which digital technologies are associated with Statistical process control (SPC)?
- RQ2: Which digital technologies are associated with products classified into groups to create better flow in production?
- RQ3: Which digital technologies are associated with Total productive/preventive maintenance (TPM)?
- RQ4: Which digital technologies are associated with pull systems in production?
- RQ5: Which digital technologies are associated with systematically working with reducing set-up times?
- RQ6: Which digital technologies are associated with employee involvement in continuous improvement?

2. LITERATURE REVIEW

2.1 Lean Production

Lean production is a concept that has evolved over many decades (Emiliani 2006), its roots may be in Henry Ford's mass production factory (Shah and Ward 2007). The philosophy, tools and techniques evolved primarily in Japan and became the Toyota Production System, later renamed Lean Production by Krafcik (1988) and subsequently popularised (Womack *et al.* 1990; Womack and Jones 1996). The organic growth of the concept by practitioners and academics meant that Lean production was not commonly defined, creating confusion about the precise definitions of its concepts (Koskela 2004). To remedy this deficit, some studies have later applied a more explicit theoretical lens. In a systematic literature review, Danese *et*

al. (2018) found that the most used lenses are contingency theory (CT), the sociotechnical systems (STS) theory and the resource-based view (RBV). In this paper we apply STS, where Lean is seen as a combination of human, organisational and technical elements, because it is particularly relevant for studies delving into the impact of Industry 4.0 (Åhlström *et al.* 2021).

Using resources for any other reason than to create value for the end customer is considered a waste and should be avoided (Emiliani 2006; Ciarniene and Vienazindiene 2012; Cifone *et al.* 2021). This focus on waste reduction is manifested through, among other things, streamlined, stable, and standardised processes; minimal inventories; the one-piece flow of products; production based on actual downstream demand; short setup times; and employees being involved in continuous improvement efforts (Chavez *et al.* 2015). For a full analysis of Lean tools, see Ciano *et al.* (2021, 1389). All these aspects can support improvements in different dimensions of operational performance (Lewis 2000; Mackelprang and Nair 2010; Marodin and Saurin 2013).

Lean production can be conceptualised at three levels: The guiding philosophy, implementation principles and the underlying practices (Čiarnienė and Vienazindienė 2012; Cifone *et al.* 2021). In this paper, we aim to measure Lean practices, and at this level Shah and Ward's (2007) framework is perhaps the most prominent. According to Shah and Ward's (2007) definition, 'Lean production is an integrated socio-technical system whose main objective is to eliminate waste by concurrently reducing or minimizing supplier, customer, and internal variability.' However, this paper focuses on the internal dimension, which is mainly about reducing process time variability (Shah and Ward 2007).

The six internal dimensions of Lean are, according to Shah and Ward (2007):

1. Production PULL: facilitating just-in-time production, including Kanban cards that serve as a signal to start or stop production.
2. Continuous FLOW: establish mechanisms that enable and ease the continuous flow of products.
3. Setup-time reduction (SETUP): reducing process downtime between product changeovers.
4. TPM: address equipment downtime and thus achieve a high level of equipment availability.
5. SPC: ensure each process will supply defect-free units to the subsequent process.
6. Employee involvement (EmpInv): Emphasise employees' role in problem solving, and their cross-functional character.

2.2 Digital Technologies

In the widest sense, digitalisation of production can be defined as 'the use of digital data and technology to automate data handling and optimise processes' (Buer *et al.* 2018, 1036). Rießmann *et al.* (2015) identified nine technological 'pillars' of I 4.0: (i) Autonomous Robots, (ii) Simulation, (iii) Horizontal and Vertical Integration, (iv) Industrial Internet of Things (IoT), (v) Cybersecurity, (vi) Cloud, (vii) Additive Manufacturing, (viii) Augmented Reality, and (ix) Big Data and Analytics. The pillars are also confirmed by Culot *et al.*'s (2020) review of I 4.0

definitions, as well as by other reviews of Industry 4.0 (Machado *et al.* 2020; Parente *et al.* 2020). In our case we researched only a subset of these technologies, selected using a discussion among academics and expert practitioners in the EMS consortium (Fraunhofer ISI, 2021). The ones included are generally used technologies, which means that some later cutting-edge technologies are excluded. These are as follows:

1. Mobile/wireless devices in production:
Mobile/wireless device use varies from the programming and operation of equipment and machinery (Rakic *et al.* 2021), to simple input devices for advanced I 4.0 systems (Tufail *et al.* 2021).
2. Digital solutions for drawings, work schedules and instructions
Digital artefacts (e.g., email messages, documents, CAD drawings, work assignments) are quite distinct from the IT tools used to produce them (e.g., email systems, productivity software, cloud-based systems). Examples include physical product prototypes, design drawings, and standardised reporting forms. There are also various types of IT-related tools, such as document archives and enterprise resource planning (ERP) systems, which can make otherwise highly complex collective actions manageable and controllable, with the potential to be utilised to facilitate the processes of knowledge transference (Fang *et al.* 2021).
3. Production planning software (e.g. ERP)
One good systematic strategy is to approach the implementation of digitalisation through production planning and control (or ERP) as it is a core production management responsibility. It encompasses decision-making processes and policies about planning (estimating, routing, scheduling and resource loading) and controls dispatching, expediting, inspection, evaluating and corrective action of production processes and resources to produce products that meet market needs in a sustainable and profitable way. Every system should be built uniquely for each company, according to Oluyisola (2021). Production planning starts with forecasting, which has several inputs (previous data, human knowledge and information) so the software is only as good as it predicts well (Schuh *et al.* 2021). Therefore, this technology greatly relies on data capture technology.
4. Digital exchange with customers/suppliers (e.g., EDI)
Companies influence and encourage their trading partners to adopt electronic data interchange (EDI) and e-procurement systems as well to increase their own benefits from its adoption. EDI is a point-to-point fixed connection and as such is more secure than e-procurement over internet. However, because of dynamic environments, it is impossible to build an EDI connection to each supplier or buyer, so many companies use password-protected websites. Whatever companies use, the cost of an order has decreased significantly, not to mention the speed of making the request (Branco *et al.* 2021).
5. Near real-time production control systems (e.g., MES)
ERP systems are typically unwieldy and do not support the real-time decision making that today's

market environments demand unlike, manufacturing execution systems (MES) and advanced planning and scheduling (APS) systems. Indeed, these systems have been developed in the last two decades to address some of these weaknesses of ERP systems. While APS systems have been associated with various potential benefits, including support for real-time decision making, the challenge is still the necessity to integrate it with an existing ERP system (Oluyisola *et al.* 2021).

6. Automated warehouses & internal logistics (WMS, RFID)
Radio frequency identification (RFID) technology has improved the operational efficiency and process flow in the distribution of warehouse management systems (WMS) around the globe (Choong *et al.* 2021). Smart warehousing aims at increasing the overall service quality, productivity and efficiency while minimising the costs and failures. Different businesses require different kinds of smart warehouses (van Geest *et al.* 2021). Warehouses play a significant role in the seamless distribution, integration and storage of items as well as in supply chain operations. Automated identification (auto-ID) technologies that include barcode and RFID provide class- or item-level visibility to facilitate effective and efficient decisions in their respective environments.
7. Product lifecycle management (PLM) systems
Many manufacturing companies have already implemented PLM systems but are not able to realize the benefits due to the lack of usage (Singh *et al.* 2021). These systems handle various kinds of engineering, business and management activities concerning a product throughout its whole lifecycle—from the inception of an intangible concept through the recycling of a finished product (Wang *et al.* 2021). However, the solutions available in practice need specific interfaces and tend to be vendor dependent (Deuter and Imort 2021).
8. VR or simulation for product design/development
Lorusso *et al.*'s (2021) research shows a large time reduction in design and prototyping when using virtual or augmented reality (VR/AR) and simulation. This means that products are faster to market, and initial revenue can be gained earlier if the product is a success.

2.3 Digital Lean

As described by Riezebos *et al.* (2009), when the focus was put on the success of Toyota Production Systems back in the late 1970s, a common misconception was that its roots and success were based on IT and automation. In reality, it was based on simplicity and robustness. On the other hand, Lean manufacturing has been characterised by a tendency towards automation since its early stages; indeed, its founder, Taiichi Ohno, stated that repetitive value-adding processes should be automated to improve the information flow and meet market demands. Since autonomy is a crucial theme in I 4.0, Lean practices can be considered as its precursor (Ciano *et al.* 2021).

Ciano *et al.* (2021) elaborate that Lean practices, with its highly streamlined process orientation with defined tasks

and times, its standardisation of work and places, and its emphasis on visual control and transparency, facilitate the implementation of I 4.0 information sharing and automation. On the other hand, several studies point out that I 4.0 technologies can boost Lean practices. They give the examples of factory integration, sensors and IoT technologies that improve Kanban, shorten cycle time and make milk runs more efficient. Ciano *et al.* (2021) further state that these technologies allow the real-time collection of data that can empower value-stream mapping and hasten the detection of waste.

Buer *et al.* (2021) states that empirical research on the link between IT and Lean has started to emerge only recently, as for example on Indian and Brazilian manufacturing firms, but this research lacks control variables. Buer *et al.*'s (2021) survey is a contribution because they researched a highly developed country (Norway) with several control variables, yet they only researched mediating or moderating effects. According to Rossini *et al.* (2019), there is still a lack of an in-depth and comprehensive pairwise analysis at a practice technology level that is able to clarify the roles of both paradigms in an LP-I 4.0 transformation. They conducted pairwise research between Lean and I 4.0 based on a limited sample, mostly from Italy. Although some quantitative studies have found a general link between Lean and digital technologies (Rossini *et al.* 2019; von Haartman *et al.* 2021), these studies generally lack detail. They do not identify which dimensions of Lean are associated with which type of technology. Studies that rectify these shortcomings tend to be case studies (e.g., Rosin *et al.* 2020), limiting the applicability of the findings to a narrower context. Others, such as Anosike *et al.* (2021) find synergic effects but only research a narrow topic, in their case IoT and Lean.

Concepts for combining Industry 4.0 and Lean have been suggested, such as Lean 4.0 (Mayr *et al.* 2018) and Lean Industry 4.0 (Ejsmont *et al.* 2018). Mayr *et al.* (2018) summarises current views on the combination of Industry 4.0 and Lean Management by dividing them into three perspectives: (1) Lean management as enabling or a prerequisite of Industry 4.0, (2) Industry 4.0 as advancing or promoting Lean management, and (3) the combination of Lean management and Industry 4.0 as a synergy creator. Buer *et al.*'s (2021) findings show that both Lean manufacturing and factory digitalisation individually contribute to improved operational performance. Ciano *et al.* (2021) and Rosin *et al.* (2020) even go so far as to state that Lean is a necessary precondition for implementing Industry 4.0 technology. They also, in line with Buer *et al.* (2021), state that not enough empirical investigation has been conducted.

Aiming to join the disciplines of Lean and Industry 4.0, Wagner *et al.* (2017) investigated I 4.0 projects at a global company within the automotive industry. Their research resulted in a matrix illustrating the impact of specific I 4.0 technologies on specific Lean principles. The specific eight I 4.0 technologies in their study were clustered into (1) data acquisition and processing, (2) machine-to-machine communication, and (3) human-machine interaction, and the eleven specific Lean principles, based on Thomopoulos (2016). Another matrix of the combination of I 4.0 tools and lean principles is put forward by Mayr *et al.* (2018), based on a literature review.

They focus on specific lean methods rather than principles and investigate a wider range of I 4.0 technologies. To exemplify their argument, they used a case of joint improvement in electric drive production.

2.3.1 Digital technologies and the six dimensions of Lean

Sanders *et al.* (2017), on a conceptual level, highlight total productive maintenance (TPM), kanban, production smoothing, automation, and waste elimination as aspects of lean manufacturing that will benefit from introducing digital technologies. Furthermore, they suggest that real-time capability, decentralisation, and interoperability are the aspects of the Industry 4.0 vision that will offer the most support to lean manufacturing. Similar studies evaluating the potential interfaces between Industry 4.0 technologies and Lean manufacturing practices are now being published regularly (e.g. Rosin *et al.* 2019; Tortorella *et al.* 2020). The potential impact of the six dimensions of Lean practices (see section 2.1.) are further elaborated in the sections below.

2.3.1.1 Pull

Analysing traditional and potentially forthcoming kanban systems using industry 4.0 technologies, El Abbadi *et al.* (2018) propose that kanban 4.0 could function in two ways – by using either smart products or smart bins to transfer orders. Pekarčíková *et al.* (2020) state that a pull system, for which kanban cards or containers are the most visible Lean component that can be combined or replaced by RFID tags (giving not only status of work-in-progress inventory but also using the broader ERP system), can provide prescriptive and analytic reports. An electronic kanban bin does not have to be physically removed from the shop floor because RFID, combined with other information technologies, gives information in real time, enabling better management and faster decision making. Kanban cards can be changed to an integrated solution, creating a gapless information flow between manufacturing order, material supply, material stock, and material consumption, where sensors detect every material movement and IoT tracks products in real time (Salvadorinho and Teixeira 2021). Enabling simulation and virtualisation via I 4.0 tools including RFID tags allows less overproduction, reduced transport, moving and inventory, as well as a lower number of mistakes (Pekarčíková *et al.* 2019).

2.3.1.2 Flow

The flow principle necessitates gathering data (via RFID or other means) and analysing it. That greatly improves management and allows faster decision making. Robotics, more specifically collaborative or even autonomous robots, are able to adjust the productive flow and act promptly, ensuring that production runs smoothly (Roy *et al.* 2020). Three-dimensional printing can be mounted near the customer's location and makes it possible to reduce distance and delivery cost, which enhances the just-in-time principle, decreasing lead times and augmenting logistics performance (Salvadorinho and Teixeira 2021).

2.3.1.3 Set-up

Set-up time is defined as the time period between the last good item produced and the first good item produced by the following production run. According to Enginarlar (2003), the aims of set-up time reduction are increasing capacity, minimising machine downtime and thus preventing capacity loss. To that end, through successful set-up time reduction, equipment downtime and capacity loss can be decreased, and machines and equipment can produce more items so production output increases. For shortening set-up times, Pekarčíková *et al.* (2019) propose a network of sensors with the ability to analyse the data in real time. In their theoretical analysis, it should contribute to lower overproduction and inventory, as well as cutting unnecessary processes and human mistakes. However, Küçük and Aldemir (2013) argue that it is not one technology that reduces set-up time rather a combination of technologies – from gathering data from sensors and RFID to advanced IoT systems. Indeed, Sheri *et al.* (2005) found that combining SMED with modern IT-based methods was effective in reducing set-up times.

2.3.1.4 TPM

TPM is another dimension of Lean that has been recently attracting attention for integration with I 4.0 technologies (Sipsas *et al.* 2016). Big data analytics, cloud-based systems, and IoT enable real-time information and data that can support productive and preventive maintenance, including simulations by digital twins or using artificial intelligence for preoptimisation of maintenance (Vinodh *et al.* 2020). Sensors and RFID data are then compared with the information from the machine and the specific work piece being processed, allowing continuous monitoring and predicting the incidence of failures. With prompt information about the equipment's state and properly triggered repair actions, a smart planner can easily keep up to date on reconfiguring production lines and save costs (Salvadorinho and Teixeira 2021). Based on case studies of four Brazilian manufacturers, Tortorella *et al.* (2021b) found that the integration of I 4.0 technologies into TPM practices has both benefits and barriers, but overall, digital technologies provide firms with enhanced tools for deploying and exploiting TPM.

2.3.1.5 SPC

Over the past decades, control charts, one of the essential tools in statistical process control (SPC), have been widely implemented in manufacturing industries as an effective approach for anomaly detection (AD). Thanks to the development of technologies like IoT and artificial intelligence (AI), smart manufacturing has become an important concept for expressing the end goal of digitalisation in manufacturing. However, even with drawing process control charts to detect anomalies quickly and in real time, there are still problems for AI to find those anomalies (Tran *et al.* 2022). For example, Bernstein (2021) suggests putting additional sensors on machines to come closer to the source of the problem. That means that in this moment digitalised SPC control charts are good for faster detection of anomalies but are still not able to detect the problem without human intervention.

2.3.1.6 Employee Involvement (EmpInv)

Previous studies on the relationship between employee involvement and the deployment of Industry 4.0 technologies show mixed results. On the one hand, some authors claim that employee-centered Lean and digitalisation represent contradictory trends (e.g. Hirsch-Kreinsen 2016), while others report an interdependency between successful implementation of Lean and I 4.0 technologies (e.g. Rossini *et al.* 2019; Cifone *et al.* 2021). As an example, Butollo *et al.* (2019) see in the current implementation of I 4.0 projects a tendency toward greater standardisation and control of work. This is in line with the concept of Lean production but neglects its participant-oriented elements such as teamwork and shop-floor-based improvement activities. Based on a bibliographic research methodology, Rosin *et al.* (2019) found in the same vein that the implementation of I 4.0 technologies does not support the Lean principles of people and teamwork. In contrast to these studies, Vereycken *et al.* (2021) show that reorganising the HR function and actively engaging employees leads to faster adoption of I 4.0 technologies. Liao and Wang, (2021) also find complementarities between lean employee engagement and adoption of sustainable digitalisation tools in a pharmaceutical company. Based on a survey of Brazilian manufacturers, Tortorella *et al.* (2021a) furthermore found that firms' employee involvement practices, as part of their continuous improvement (CI) programmes, have a positive mediating effect on the relationship between the use of I 4.0 technologies, specifically process technologies, and operational performance improvements. They conclude that I 4.0 might support employees in CI and strengthen the involvement of employees in high-tech transformation.

3. METHODS

3.1 Digital Lean

3.1.1 Digital Technologies and the Six Dimensions of Lean

The Lean constructs are based on Shah and Ward (2007) but limited to the internal dimensions. Moreover, items that were discarded in Shah and Ward's (2007) factor analyses were not included in the questionnaire. This resulted in 24 items, covering six dimensions of Lean. Another deviation from the original constructs is that the items were measured on a four-point scale in order to fit better with the overall design of the EMS. The value 0 corresponds to 'not at all', 1 to 'low extent', 2 to 'medium extent' and 3 to 'high extent'. The items are thus measured on an ordinal scale, although the original Shah and Ward (2007) construct is also measured on an ordinal scale, albeit a five-point one. The mean value for each of the six Lean dimensions is displayed in **Figure 1**. TPM and Flow seem to be the most common Lean practices, SPC and Pull the least common, but the differences are not statistically significant.

Due to the ordinal nature of the scale, it is more appropriate to use non-linear principal component analysis (NLPCA), rather than ordinary principal component analysis (PCA) or factor analysis (Linting *et al.* 2007). NLPCA is similar to ordinary PCA but uses quantification, a process where the original values are replaced by optimally scaled ones, while maximising the original variables' variance. After the variables have been

quantified, the procedure is the same as the ordinary PCA (Linting *et al.* 2007). The SPSS package ‘optimal scaling’ was used, where the variables were set to ordinal and discretised using the ranking methods. After two items, Pull1 and Emp4, were removed due to cross loading, all the

remaining items satisfactorily converged on six dimensions. All secondary loadings are much lower than the primary loading (**Table 1**). Cronbach’s alpha is between .72 and .85 (**Table 1**).

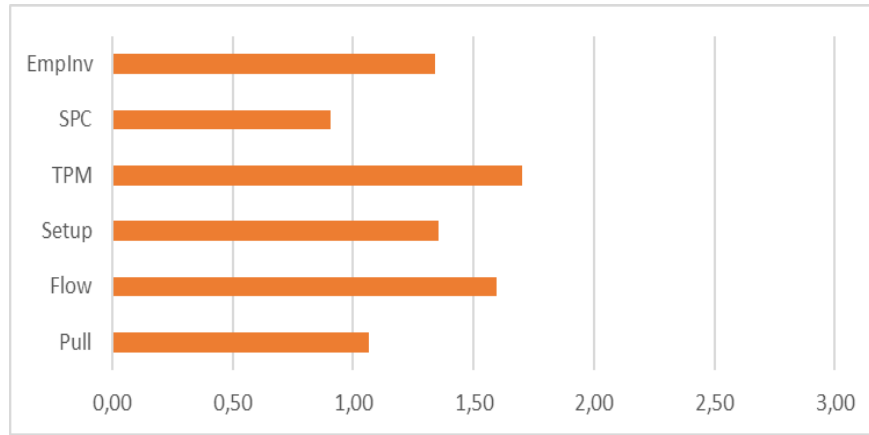


Figure 1 Relative use of lean practices (N=195)

Table 1 Nonlinear principal component analysis of the lean construct (N=195, KMO=0.829, bartlett test sign p<0.01, total variance explained=69%, values under .30 are suppressed)

	Component					
	SPC	Flow	TPM	Pull	Setup	Emplnv
Pull2				0.876		
Pull3				0.909		
Pull4				0.783		
Flow1		0.720				
Flow2		0.737				
Flow3		0.777				
Flow4		0.773				
Setup1	0.351				0.775	
Setup2					0.793	
Setup3					0.612	
SPC1	0.734					
SPC2	0.781				0.318	
SPC3	0.754					
SPC4	0.632				0.335	
SPC5	0.628	0.301				
Emp1						0.775
Emp2						0.773
Emp3				0.375	0.324	0.652
TPM1			0.732			
TPM2			0.724			0.334
TPM3			0.842			
TPM4	0.352		0.688			
Initial eigenvalue	6.71	2.54	1.89	1.62	1.31	1.04
Cronbach's alpha	0.85	0.80	0.84	0.84	0.72	0.72

3.1.2 Digital Technologies and the Six Dimensions of Lean

This paper considers eight digital technologies used in production (see section 2.2). The prevalence of these technologies among the surveyed companies is displayed in figure 2. These eight variables are used individually in descriptive and correlation analyses. As the items are too

numerous and some highly correlated, the numbers need to be reduced to facilitate a multiple regression analysis. As with the Lean items, the digital items are measured on an ordinal scale, which means a similar non-linear PCA is appropriate (Linting *et al.* 2007). The result of the non-linear PCA is displayed in Table 2.

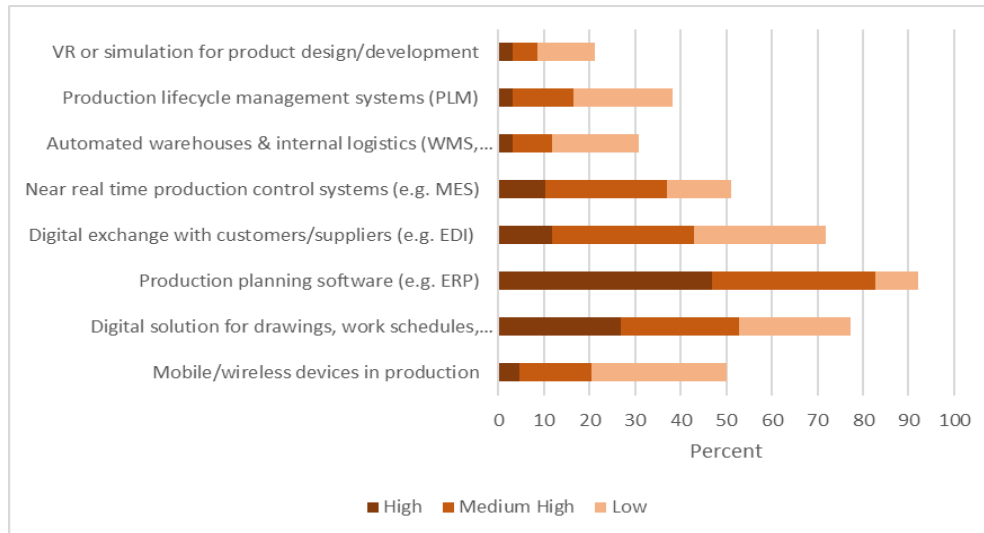


Figure 2 Prevalence of digital technologies in production (N=228)

Table 2 Nonlinear PCA of digital technologies (KMO=0.76, Bartlett test sign p<0.01, total variance explained=53% N=224, values under .35 are suppressed)

	Component	
	1 Production IT	2 Other Tech
Mobile/wireless devices in production		0.685
Digital solution for drawings, work schedules, instructions	0.727	
Production planning software (e.g. ERP)	0.774	
Digital exchange with customers/suppliers (e.g. EDI)	0.744	
Near real-time production control systems (e.g. MES)	0.693	0.313
Automated warehouses & internal logistics (WMS, RFID)		0.669
Product lifecycle management systems (PLM)		0.738
VR or simulation for product design/development		0.621
Initial eigenvalue	2.97	1.28
Cronbach's alpha	0.75	0.64

3.1.3 Control Variables

In the regression analysis, four control variables were included to take into account the manufacturing plant context, as it may have a major impact on the extent of Lean (Lewis 2000) and digitalisation (European Commission 2016). Companies often need digitalisation in order to manage increased customisation with shorter production runs, complexity in the production as well as managing inventory effectively (Vinodh *et al.* 2021). Three controls related to these concerns were thus included: batch size, complexity of the manufactured product, and production system (i.e., whether the product is made to stock or made to order). These three variables are dummies, with 1 signifying a complex product, a large batch size and a made-to-stock production system. The fourth control variable is company size in terms of sales, as this has also been shown to have an impact on

level of digitalisation of production (e.g., European Commission 2016). As there was a relatively high number of missing values for company size, the variable was complemented by looking up respective firms' annual reports. In some instances, the number of employees for the manufacturing unit could not be obtained, and in those cases the number for the whole company was used. The values for sales are highly skewed and have a very high value for kurtosis, as there are a relatively small number of large firms and many small ones. One suitable technique to improve the distribution of the data is to use the logarithmic value (NIST/SEMATECH 2014). The logarithmic (Ln) value of size is thus used in further analysis. This value does indeed fall within -2 and +2 of both skew and kurtosis, which is regarded as the 'safe' zone (George and Mallery 2010).

4. RESULTS

The results section is divided into two parts: (1) results from the correlation analysis and (2) results from the multiple regression analyses.

4.1 Correlation

In the correlation analysis, the six components (factors) are correlated with the eight selected digital

technologies. Spearman correlation is used, as the digital technologies are measured on an ordinal scale (**Table 3**).

The results show that in around half of all instances Lean components and digital tools are significantly correlated. Of the Lean components, SPC and Pull show most significant correlations, as does PLM and Production planning software among the digital tools. The results will be further discussed in the Discussion section.

Table 3 Correlation analysis (N=185 to 188, Spearman correlations, **p<0.01. *p<0.05)

	SPC	Flow	TPM	Pull	Setup	Emp Inv
Mobile/wireless devices in production	0.016	-0.085	0.138	0.196**	0.254**	0.139
Digital solution for drawings, work schedules, instructions	0.178*	0.049	0.126	.342**	0.064	0.044
Production planning software (e.g. ERP)	0.226**	0.216**	0.070	0.273**	0.149*	-0.044
Digital exchange with customers/suppliers (e.g. EDI)	0.109	0.000	0.174*	0.261**	0.172*	0.035
Near real-time production control systems (e.g. MES)	0.177*	0.120	0.251**	0.125	0.089	-0.015
Automated warehouses & internal logistics (WMS, RFID)	0.202**	0.019	0.088	0.098	0.076	0.149*
Production lifecycle management systems (PLM)	0.302**	0.198**	0.150*	0.193**	0.011	0.145*
VR or simulation for product design/development	0.294**	0.251**	0.007	0.175*	-0.016	0.141

4.2 Regression Analysis

While the correlation analysis identifies which technologies are associated with different dimensions of Lean, it does not account for the effects of firm size and variations in production systems. To address this limitation, a multiple regression analysis will be performed, incorporating relevant control variables. The next phase of the analysis involves six separate multiple regression analyses, treating the six Lean dimensions extracted from

the NLPCA (see section 3.1.1) as dependent variables (see **Table 4**). The independent variables include the four control variables introduced in section 3.1.3 and the two components of the NLPCA described in section 3.1.2. This analysis will demonstrate the simultaneous impact of the two dimensions of digital technologies, “production IT” and “other tech,” while accounting for variations in firm size and production systems.

Table 4 Multiple regression analysis (**p<0.01. *p<0.05, N=185 to 188)

	SPC	Flow	TPM	Pull	Setup	Emplnv
Control variables						
Size (Ln sales)	-0.06	-0.09	0.02	0.37**	0.04	-0.12
Make-to-stock	-0.08	0.05	0.03	0.22**	-0.06	0.15
Lg. batch size	0.12	0.11	0.12	-0.27**	0.08	0.04
Complex product	-0.01	-0.07	0.15	0.03	0.06	0.12
Digital technologies						
Production IT	0.23**	0.02	0.17*	0.32**	0.13	-0.01
Other Tech	0.39**	0.28**	0.08	0.12	0.15	0.26**
R ²	0.23	0.11	0.08	0.30	0.04	0.12
Adjusted R ²	0.20	0.08	0.05	0.28	0.01	0.09
F-value	8.69**	3.58**	2.43*	12.60**	1.35	4.02**

Table 4 shows that five out of six regression analyses yield significant F-values, although some regression models have relatively low R² values. The SPC and Pull models have high R² values and significant contributions from at least one of the technology dimensions. Specifically, the SPC model demonstrates a strong contribution from both “production IT” and “other tech,” while only “production IT” is significantly associated with the Pull model. Although Flow and Emplnv have lower R² values, they are both strongly associated with “other tech.” In contrast, the TPM and Setup models show weak R² values and weak or nonexistent associations with the technology variables. After checking for potential multicollinearity problems

(which were absent) and confirming that the residuals are randomly distributed, we conclude that there are highly significant associations between four of the Lean dimensions and the technologies employed in production. These results will be further discussed in the next section.

5. DISCUSSION

5.1 Pull

In the regression analysis (**Table 4**), it was evident that pull is strongly related to production IT. The correlation analysis (**Table 3**) indicated that a digital solution for drawings, work schedules and instructions,

production planning software, and digital exchange with customers/suppliers are particularly strongly associated with pull. ERP systems was indeed predicted by the literature to be a good match to pull systems by Pekarcikova *et al.* (2020), as was a match between integrated IT solution and pull (Salvadorinho and Teixeira 2021). One explanation could be that firms with extensive use of ERP or other production-related IT systems have a more orderly and structured production environment, making them more prepared for a pull-based production system. Simulation/virtualisation and pull were also linked in the literature (Pekarcikova *et al.* 2020), and the connection was also confirmed by this study, although the connection was not as strong as the previously mentioned IT solutions. Moreover, theory also predicted a strong association between RFID and pull (Pekarcikova *et al.* 2020), but that could not be confirmed in this study. Furthermore, the results show that pull is also strongly associated with the production context: Large companies with make-to-stock production of relatively small batch sizes are particularly likely to adopt pull production systems.

5.2 Flow

Flow is significantly associated with what was called “other tech” in the regression analysis, whereas the correlation analysis reveals that this association concerns particularly PLM and VR or simulation for product design/development. The reviewed literature did not predict such an association, whereas the predicted associations between automated warehouses and flow (Roy *et al.* 2020) could not be confirmed. The reason for the observed strong associations could be because both of these technologies are related to the product rather than production and the items measuring flow were related to how products are classified and managed in the production flow. It is plausible that companies that have PLM or VR for their products also tend to be more product focused in their production and thus classify similar products into groups with similar processing and routing requirements.

5.3 Set-up

The regression analysis (Table 4) shows that set-up is not significantly related to either type of digital technology. Table 3, does, however show some significant correlation, most notably with mobile/wireless devices in production. Pekarčíková *et al.* (2019) proposed that networks of sensors and an ability to analyse data in real time would be beneficial for shortening set-up times, whereas Küçük and Aldemir (2013) argued that combinations of technologies rather than single technologies are most effective for reducing set-up times. It was thus expected that some impact of the broad range of digital technologies included in this survey would be observed. It is possible that firms have digitalised existing production lines in order to improve efficiency, while the process of setting up the machinery has remained largely the same. It is even possible that more technological add-ons to existing production machinery will even increase set-up times as complexity increases.

5.4 TPM

TPM is significantly associated with production IT (Table 4), and in particular EDI and near real-time production control systems (e.g. MES) (Table 3). Salvadorinho and Teixeira (2021) have emphasised that just as information about equipment state can trigger repair actions, a smart planner can be easily updated on reconfiguring production lines and save costs. In particular, MES can provide real-time information about equipment, making it possible to schedule maintenance before breakdown occur, thus explaining the strong association with TPM. The reason EDI is so strongly associated with TPM is less clear: it could be that by integrating customers and suppliers more effectively, the company may be better able to identify an available time to conduct preventive maintenance.

5.5 SPC

SPC is the only Lean component that is significantly associated with both production IT and other tech (Table 4). Moreover, the correlation analysis (Table 3) shows that SPC is significantly related to six of the eight digital technologies, and particularly strongly to PLM, VR, and production planning software. It is important to note that the SPC variable consists of five items: (1) equipment/processes for SPC, (2) statistical techniques to reduce process variance, (3) charts showing defect rates, (4) fishbone diagrams for quality problems, and (5) process capability studies before product launch. One explanation for the strong results is that companies using these techniques extensively are likely to be more systematic and quality conscious than the average firm, and thus more likely to adopt both digital and analogue techniques that allow them to monitor processes and raise quality. Another explanation is that companies are using IT systems to extract data for their SPC efforts.

In terms of quality, Tran *et al.* (2022) reported that with drawing process control charts to detect anomalies quickly and in real time, there are still problems for AI to find those anomalies, highlighting the continual need for manual SPC. Bernstein (2021) proposed putting additional sensors on machines to come closer to the source of the problem, suggesting that digitalised SPC control charts are good for faster detection of anomalies but are still not able to detect the problem without human intervention. Our findings suggest that companies realise the benefits of adopting new technologies, while keeping their time-tested SPC-based quality systems.

5.6 Employee Involvement in CI

The multiple regression analysis in Table 4 shows that employee involvement in CI is significantly associated with the use of ‘other tech’, whereas the correlation analysis shows that this association particularly concerns automated warehouses and internal logistics (WMS, RFID), as well as PLM systems. The correlations are relatively weak although significant at $p < .05$.

At first sight, it may be surprising that the connection between digital technologies and employee involvement in CI is not stronger than the results indicate, but previous literature has indeed reported contradictory findings. For example, Rosin *et al.* (2019) found that the implementation

of Industry 4.0 technologies did not support the Lean principles of people and teamwork, whereas Vereycken *et al.* (2021) found that reorganising the HR function and actively engaging employees leads to faster adoption of I 4.0 technologies. Our findings suggest that there is no universal link between employee involvement in CI and digital technologies, but that there are some connections to individual technologies, such as PLM. It is plausible that employees particularly involved in CI may be more value-driven and favour technologies that align with those values. As the connections found in this study were not particularly strong, this topic would be suitable to study in more detail in order to get a more conclusive answer.

6. CONCLUSIONS

The purpose of this paper was to explore which of the common digital technologies used in production are associated with which internal Lean dimensions. The analysis divided the technologies into two general types of digital technologies: ‘production IT’ and ‘other tech’. The former is significantly associated with SPC, TPM and pull, whereas the latter is significantly associated with SPC, flow and employee involvement in CI (Table 4). In more detail, we found significant correlations between around half of the digital technologies and different dimensions of Lean (Table 3). The strongest correlations were between SPC and PLM and VR, between flow and VR, between TPM and near real-time production control systems, between pull and digital solutions for drawings, production planning software and digital exchange with customer/suppliers. The discussion highlighted possible explanations for the observed results.

The overall conclusion is thus that the internal dimensions of Lean are intertwined with the usage of digital technologies in production. The literature suggested that the commonality of the two concepts can be divided into three perspectives: (1) Lean as an enabler of digitalisation, (2) digitalisation as a promoter of Lean, and (3) Lean and digitalisation as a synergy creator (Mayr *et al.* 2018). While this paper acknowledged all three perspectives as plausible, it has taken the second perspective, digitalisation as an enabler.

The paper thus contributes to the literature (Ciano *et al.* 2021; Cifone *et al.* 2021; Rosin *et al.* 2020) on how digital technologies can be combined with Lean, by both confirming the strong link between the two concepts and pinpointing which dimensions of Lean are most strongly associated with which types of digital technologies. This has been accomplished by using a robust, well-tested, six-dimensional Lean framework and eight common digital technologies, using a survey with responses from more than 180 manufacturing plants. The paper thus not only provides more details on the linkages between multiple dimensions of Lean and digital technologies but also facilitates more research into the topic. The findings of the paper have a strong relevance for practitioners who contemplate investments into digital technologies with the aim of improving certain Lean dimensions of their manufacturing operations.

We suggest that the results could serve as a basis for future research along two routes. First, there are some previous qualitative studies investigating the link between

digital tools and Lean (e.g., Ciano *et al.* 2021; Cifone *et al.* 2021), but there is still a need for a deeper understanding of the mechanisms between the strong relationship between the two. This paper provides an overview of some of the connections among these concepts, but future studies could offer some concrete examples. Second, the study presented in this paper did not investigate the effects of companies’ investments and internal efforts in the Lean and digital dimensions. Are some of these combinations more likely to lead to increased performance? What type of performance, productivity, quality, flexibility or sustainability is associated with what configuration of digital Lean?

REFERENCES

- Åhlström, P., Danese, P., Hines, P., Netland, T. H., Powell, D., Shah, R., Thüerer, M., and van Dun, D. H. (2021). "Is Lean a Theory? Viewpoints and Outlook." *International Journal of Operations & Production Management*, 41 (12), pp. 1852-1878. <https://doi.org/10.1108/IJOPM-06-2021-0408>.
- Anosike, A., K. Alafropatis, J. A. Garza-Reyes, A. Kumar, S. Luthra, and Rocha-Lona, L. (2021). "Lean Manufacturing and Internet of Things – A Synergetic or Antagonist Relationship?" *Computers in Industry*, 129, p. 103464.
- Bernstein, J. (2021). "High Quality with Statistical Process Control 4.0 in Automation." In *Creating Innovation Spaces: Impulses for Start-ups and Established Companies in Global Competition*, edited by Nestle, V.; Glauner, P. and Plugmann, P., pp. 169-181, Cham, Springer
- Branco, F., R. Gonçalves, Moreira, F., Au-Yong-Oliveira, M., and Martins, J. (2021). "An Integrated Information Systems Architecture for the Agri-Food Industry." *Expert Systems*, 38 (4): e12599.
- Buer, S. V., Fragapane, G. I. and Strandhagen, J. O. (2018). "The Data-Driven Process Improvement Cycle: Using Digitalization for Continuous Improvement." *IFAC-PapersOnLine*, 51 (11), pp. 1035-1040.
- Buer, S. V., Semini, M., Strandhagen, J. O., and Sgarbossa, F. (2021). "The Complementary Effect of Lean Manufacturing and Digitalisation on Operational Performance." *International Journal of Production Research*, 59 (7), pp. 1976-1992.
- Butollo, F., Jürgens, U. and Krzywdzinski, M.. (2019). "From Lean Production to Industrie 4.0: More Autonomy for Employees?" In *Digitalization in Industry*, edited by U. Meyer, S. Schaupp and D. Seibt, 61-80. London: Palgrave Macmillan.
- Chavez, R., Yu, W., Jacobs, M., Fynes, B., Wiengarten, F. and Lecuna, A. (2015). "Internal Lean Practices and Performance: The Role of Technological Turbulence." *International Journal of Production Economics*, 160, pp. 157-171.
- Choong, C. S., Nasir, A. F. A., Majeed, A. P. A., Zakaria, M. A. and Razman, M. A. M. (2021). "Automatic Identification and Categorize Zone of RFID Reading in Warehouse Management System." In *Advances in Mechatronics, Manufacturing, and Mechanical Engineering*, edited by Zakaria, M. A., Majeed, A. P. A., & Hassan, M. H. A., 194-206. Singapore: Springer.
- Ciano, M. P., Dallasega, P., Orzes, G., and Rossi, T. (2021). "One-to-one Relationships between Industry 4.0 Technologies and Lean Production Techniques: A Multiple Case Study." *International Journal of Production Research*, 59 (5), pp. 1386-1410.
- Čiarnienė, R. and Vienažindienė, M. (2012). "Lean Manufacturing: Theory and Practice." *Economics and Management*, 17 (2), pp. 726-732.
- Cifone, F. D., Hoberg, K., Holweg, M. and Staudacher, A. P. (2021). "Lean 4.0: How Can Digital Technologies Support

- Lean Practices?" *International Journal of Production Economics*, 241, 108258.
- Culot, G., Nassimbeni, G. Orzes, G., and Sartor, M. (2020). "Behind the Definition of Industry 4.0: Analysis and Open Questions." *International Journal of Production Economics*, 226, 107617.
- Danese, P., Manfè, V. and Romano, P. (2018). "A Systematic Literature Review on Recent Lean Research: State-of-the-Art and Future Directions." *International Journal of Management Reviews*, 20 (2), pp. 579-605.
- Deuter, A. and Imort, S. (2021). "Product Lifecycle Management with the Asset Administration Shell." *Computers*, 10 (7): 84.
- Ejsmont, K., Gladysz, B., Corti, D. Castaño, F., Mohammed, W.A., and Martinez Lastra, J. L.. (2020). "Towards 'Lean Industry 4.0' - Current trends and future perspectives." *Cogent Business & Management*, 7 (1), pp. 1–32.
- El Abbadi, L., El Manti, S., Houti, M. and Elrhanimi, S. (2018). "Kanban System for Industry 4.0 Environment." *International Journal of Engineering & Technology*, 7 (16), pp. 60-65.
- Emiliani, M.L. (2006), 'Origins of Lean Management in America', *Journal of Management History*, 12(2), pp. 167–184.
- European Commission (2016). *Digitalisering av den europeiska industrin. Hur vi kan utnyttja den inre marknadens alla möjligheter* [Digitalisation of European industry. How We Can Take Advantage of All the Opportunities of the Inner Market]. Report from the Commission to the European Parliament, Brussels.
- Fang, Y., Neufeld, D., & Zhang, X. (2022) "Knowledge Coordination Via Digital Artefacts in Highly Dispersed Teams", *Information Systems Journal*, 32(3), pp. 520-543.
- Fraunhofer ISI (2021), *European Manufacturing Survey*, <https://www.isi.fraunhofer.de/en/themen/wertschoepfung/fems.html>, accessed 2021-12-20
- George, D. and Mallery, M. (2010). *SPSS for Windows Step by Step: A Simple Guide and Reference, 17.0 Update*, 10th ed. Boston: Pearson.
- Hirsch-Kreinsen, H. (2016). "Digitization of Industrial Work: Development Paths and Prospects." *Journal for Labour Market Research*, 49, pp. 1–14.
- Knoppen, D., M. Akın Ateş, A. Brandon-Jones, D. Luzzini, E. van Raaij, E., and Wynstra, F. (2015). "A Comprehensive Assessment of Measurement Equivalence in Operations Management." *International Journal of Production Research*, 53 (1): 166-182. doi: 10.1080/00207543.2014.944629.
- Koskela, L. J. (2004). "Moving On—Beyond Lean Thinking." *Lean Construction Journal*, 1 (1), pp. 24-37.
- Krafcik, J. F. (1988). "Triumph of the Lean Production System." *Sloan Management Review* 30 (1), pp. 41–52.
- Küçük, E. and Aldemir, G. (2013). "The Importance of Introducing Set-Up Time Reduction to Industry 4.0." *BİLDİRİLER KİTABI*, 180.
- Lay, G., Copani, G., Jäger, A., and Biege, S.. (2010). "The Relevance of Service in European Manufacturing Industries." *Journal of Service Management*, 20 (5), pp. 715-726.
- Lewis, M. A. 2000. "Lean Production and Sustainable Competitive Advantage." *International Journal of Operations & Production Management*, 20 (8), pp. 959-978.
- Liao, M. H. and Wang, C.T. (2021). "Using Enterprise Architecture to Integrate Lean Manufacturing, Digitalization, and Sustainability: A Lean Enterprise Case Study in the Chemical Industry." *Sustainability*, 13 (9), pp. 4851.
- Linting, M., J. Meulman, J., Groenen P. J., and van der Kooij, A. J. (2007). "Nonlinear Principal Components Analysis: Introduction and Application." *Psychological Methods*, 12 (3), pp. 336-358.
- Lorusso, M., Rossoni, M., Carulli, M., Bordegoni, M. and Colombo, G. (2021). "A Virtual Reality Application for 3D Sketching in Conceptual Design." *Computer Aided Design*, 19(12), pp. 256-268
- Lu, Y. (2017). "Industry 4.0: A Survey on Technologies, Applications and Open Research Issues." *Journal of Industrial Information Integration*, 6, pp. 1-10.
- Machado, C. G., Winroth, M. P. and Ribeiro da Silva, E. H. D. (2020). "Sustainable Manufacturing in Industry 4.0: An Emerging Research Agenda." *International Journal of Production Research*, 58 (5), pp. 1462-1484.
- Mackelprang, A. W. and Nair, A. (2010). "Relationship between Just-in-time Manufacturing Practices and Performance: A Meta-Analytic Investigation." *Journal of Operations Management*, 28 (4), pp. 283-302.
- Marley, K.A. and Ward, P.T. (2013), 'Lean Management as a Countermeasure for "Normal" Disruptions', *Operations Management Research*, 6 (1-2), pp. 44–52.
- Marodin, G. A. and Saurin, T. A. (2013). "Implementing Lean Production Systems: Research Areas and Opportunities for Future Studies." *International Journal of Production Research*, 51 (22), pp. 6663-6680.
- Mayr, A., M. Weigelt, A. Kühl, S. Grimm, A. Erll, M. Potzel, and J. Franke. (2018). "Lean 4.0—A Conceptual Conjunction of Lean Management and Industry 4.0." *Procedia CIRP*, 72, pp. 622–628.
- Moeuf, A., Lamouri, S., Pellerin, R., Tamayo-Giraldo, S., Tobon-Valencia, E., and Eburdy, R. (2020). "Identification of Critical Success Factors, Risks and Opportunities of Industry 4.0 in SMEs." *International Journal of Production Research*, 58 (5), pp. 1384-1400.
- NIST/SEMATECH (2014). *E-Handbook of Statistical Methods*. <http://www.itl.nist.gov/div898/handbook/>.
- Oluyisola, O. E. (2021). *Towards Smart Production Planning and Control: Frameworks and Case Studies Investigating the Enhancement of Production Planning and Control Using Internet-of-Things, Data Analytics and Machine Learning*, Doctoral Thesis, NTNU -Norwegian University of Science and Technology, Trondheim, Norway
- Oluyisola, O. E., Bhalla, S., Sgarbossa, F. and Strandhagen, J. O. (2021). "Designing and Developing Smart Production Planning and Control Systems in the Industry 4.0 Era: A Methodology and Case Study", *Journal of Intelligent Manufacturing*, 33(1), pp. 311-332.
- Parente, M., Figueira, G., Amorim, P. and Marques, A. (2020). Production Scheduling in the Context of Industry 4.0: Review and Trends. *International Journal of Production Research*, 58 (17), pp. 5401-5431.
- Palčić, I., & Prester, J. (2020). Impact of Advanced Manufacturing Technologies on Green Innovation. *Sustainability*, 12(8), 3499.
- Pekaričková, M., Trebuňa, P. and Kliment. M. (2019). "Digitalization Effects on the Usability of Lean Tools." *Acta Logistica*, 6 (1), pp. 9-13.
- Pekarcikova, M., Trebuna, P., Kliment, M. and Rosocha, L. (2020). «Material Flow Optimization through E-kanban System Simulation." *International Journal of Simulation Modelling*, 19 (2), pp. 243-254.
- Rakic, S., Pavlovic, M. and Marjanovic, U. (2021). "A Precondition of Sustainability: Industry 4.0 Readiness." *Sustainability*, 13 (12), pp. 6641.
- Riezebos, J., Klingenberg, W. and Hicks, C. (2009). "Lean Production and Information Technology: Connection or Contradiction?" *Computers in Industry*, 60, pp. 237–247.
- Rosin, F., P. Forget, S. Lamouri, and R. Pellerin. (2020). "Impacts of Industry 4.0 Technologies on Lean Principles." *International Journal of Production Research*, 58 (6), pp. 1644-1661.

- Rossini, M., Costa, F., Tortorella, G. L. and Portioli-Staudacher, A. (2019). "The Interrelation between Industry 4.0 and Lean Production: An Empirical Study on European Manufacturers." *The International Journal of Advanced Manufacturing Technology*, 102, pp. 3963–3976.
- Roy, R. B., D. Mishra, S. K. Pal, T. Chakravarty, S. Panda, Chandra, M. G. and Pal, A. (2020). "Digital Twin: Current Scenario and a Case Study on a Manufacturing Process." *The International Journal of Advanced Manufacturing Technology*, 107 (9), pp. 3691-3714.
- Rüßmann, M., Lorenz, M., Gerbert, P., Waldner, M., Justus, J., Engel, P. and Harnisch, M. (2015). "Industry 4.0: The Future of Productivity and Growth in Manufacturing Industries." *Boston Consulting Group*, 9 (1), pp. 54-89.
- Rüttimann, B. G. and Stöckli, M. T. (2016). "Lean and Industry 4.0: Twins, Partners or Contenders? A Due Clarification Regarding the Supposed Clash of Two Production Systems." *Journal of Service Science and Management*, 9 (6), pp. 485–500.
- Salvadorinho, J. and Teixeira, L. (2021). "Stories Told by Publications about the Relationship between Industry 4.0 and Lean: Systematic Literature Review and Future Research Agenda." *Publications*, 9 (3), pp. 29.
- Sanders, A., K. R. Subramanian, T. Redlich, and J. P. Wulfsberg. (2017). "Industry 4.0 and Lean Management—Synergy or Contradiction?", in *Advances in Production Management Systems. The Path to Intelligent, Collaborative and Sustainable Manufacturing: IFIP WG 5.7 International Conference, APMS 2017, Hamburg, Germany, September 3-7, 2017, Proceedings, Part II* (Vol. 514), edited by Lödding, H., Riedel, R., Thoben, K. D., Von Cieminski, G., & Kiritsis, D. (Springer, 341-349. Cham, Switzerland: Springer.
- Schuh, G., A. Güzlaff, M. Schmidhuber, and D. Rolfes. (2021). "External Factors Influencing Production Planning and Control System Acceptance: A Meta-Analytical Approach." In *2021 IEEE 8th International Conference on Industrial Engineering and Applications (ICIEA)*, pp. 321-330.
- Shah, R. and Ward, P. T. (2003). "Lean Manufacturing: Context, Practice Bundles, and Performance." *Journal of Operations Management*, 21 (2), pp. 129–149.
- Shah, R. and Ward, P. T.. (2007). "Defining and Developing Measures of Lean Production." *Journal of Operations Management*, 25 (4), pp. 785–805.
- Sheri C. T. and Bohn, R. E. (2005). "Setup Time Reduction for Electronics Assembly: Combining Simple (SMED) and IT-Based Methods." *Production and Operations Management*, 14 (2), pp. 205-217.
- Singh, S., Misra, S. C. and Kumar, S. (2021). "Institutionalization of Product Lifecycle Management in Manufacturing Firms." *IEEE Transactions on Engineering Management*, doi: 10.1109/TEM.2021.3097040
- Sipsas, K., Alexopoulos, K., Xanthakis, V. and Chryssolouris, G. (2016). "Collaborative Maintenance in Flow-Line Manufacturing Environments: An Industry 4.0 Approach." *Procedia CIRP*, 55, pp. 236-241.
- Tortorella, G., R. Miorando, R. Caiado, Nascimento, D. and Portioli Staudacher, A. (2021a). "The Mediating Effect of Employees' Involvement On The Relationship Between Industry 4.0 And Operational Performance Improvement." *Total Quality Management & Business Excellence*, 32 (1-2), pp. 119-133.
- Tortorella, G., F. S. Fogliatto, P. A. Cauchick-Miguel, Kurnia, S., and Jurburg D. (2021b). "Integration of Industry 4.0 Technologies into Total Productive Maintenance Practices." *International Journal of Production Economics*, 240, pp. 108224.
- Tortorella, G. L., N. Pradhan, E. Macias de Anda, Trevino Martinez, S., Sawhney, R., and Kumar, M. (2020). "Designing Lean Value Streams in the Fourth Industrial Revolution Era: Proposition of Technology-Integrated Guidelines." *International Journal of Production Research*, 58 (16), pp. 5020-5033.
- Tran, P. H., Ahmadi Nadi, A. Nguyen T. H., Tran, K. D. and Tran, K. P. (2022). "Application of Machine Learning in Statistical Process Control Charts: A Survey and Perspective." In *Control Charts and Machine Learning for Anomaly Detection in Manufacturing*, edited by K.M Tran 7-42. Cham: Springer.
- Tufail, A., Namoun, A., Alrehaili, A. and Ali, A. (2021). "A Survey on 5G Enabled Multi-Access Edge Computing for Smart Cities: Issues and Future Prospects." *International Journal of Computer Science & Network Security*, 21 (6), pp. 107-118.
- van Geest, M., Tekinerdogan, B., and Catal, C. (2021). "Design of a Reference Architecture for Developing Smart Warehouses in Industry 4.0." *Computers in Industry*, 124, pp. 103343.
- Vereycken, Y., M. Ramioul, Desiere, S. and Bal, M. (2021). "Human Resource Practices Accompanying industry 4.0 in European Manufacturing Industry." *Journal of Manufacturing Technology Management*. 32(5), pp. 1016-1036
- Vinodh, S., J. Antony, R. Agrawal, and J. A. Douglas. (2021). "Integration of Continuous Improvement Strategies with Industry 4.0: A Systematic Review and Agenda for Further Research." *The TQM Journal*, 33 (2), pp. 441-472.
- von Haartman, R., Bengtsson L., and Niss, C.. (2021). "Lean Practices and the Adoption of Digital Technologies in Production." *International Journal of Services and Operations Management*, 40 (2), pp. 286-304.
- Wagner, T., Herrmann, C., and Thiede, S. (2017). "Industry 4.0 Impacts on Lean Production Systems." *Procedia CIRP*, 63, pp. 125–131.
- Wang, L., Liu, Z., Liu, A., and F. Tao. (2021). "Artificial Intelligence in Product Lifecycle Management." *The International Journal of Advanced Manufacturing Technology*, 114 (3-4), pp. 1-26.
- Womack, J. P. and Jones, D.T. (1996). *Lean Thinking: Banish Waste and Create Wealth in Your Corporation*. New York: Simon & Schuster.
- Womack, J. P., Jones, D.T. and Roos, D. (1990). *The Machine that Changed the World*. New York: Harper Perennial.

Robin von Haartman is an Associate Professor (Docent) at the University of Gävle, where he researches and teaches supply chain management and related subjects. He received his PhD from KTH Royal Institute of Technology. His research currently covers issues such as sustainable operations and supply chains and manufacturing strategy. The results of previous studies have been published in journals such as *International Journal of Operations and Production Management*, *International Journal of Logistics: Research and Applications* and *International Journal of Physical Distributions and Logistics Management*.

Jasna Prester is full professor at University of Zagreb, Faculty of Business and Economics where she teaches Operations Management, Supply Chain Management and Service Operations Management. She got her PhD from University of Zagreb, Faculty of Business and Economics. In her academic's life of 20 years she has more than 100 publications and some in top

journals like IEEE Transactions on Engineering Management, International Journal of Operations & Production Management, Total Quality Management & Business Excellence.

Lars Bengtsson is Professor in Innovation Management at the University of Gävle, Sweden, and Docent (associate professor) at KTH in Stockholm. The research focuses on open innovation, Lean transformation, knowledge integration, and manufacturing and supply chains strategies. His publications appear in journals such as International Journal of Production and Operations Management, Production Planning and Control, Technological Forecasting & Social Change, Creativity and innovation management, International Journal of Technology Management, and Journal of Evolutionary Economics.

Camilla Niss is an Affiliated Researcher at the University of Gävle, Sweden. She received her PhD from KTH (The Royal Institute of Technology) in Stockholm. Her main research interests are project management, innovation and digitalization.