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Adopting Industry 4.0 technologies through lean tools: evidence from the European Manufacturing Survey

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Abstract

Purpose – In recent years, the emergence of Industry 4.0 technologies as a way of increasing productivity has attracted the attention of the manufacturing industry. This study aims to investigate the relationship between Industry 4.0 technologies and lean tools (LTs) by measuring how the internalisation of LTs influences the adoption of Industry 4.0 technologies and how the synergy between them helps improve productivity in European manufacturing firms.

Design/methodology/approach – Results from 1,298 responses were used to analyse linear regression and study the correlation between the use of LTs and Industry 4.0 technologies.

Findings – Results show that the companies analysed tend to implement more Industry 4.0 technologies when their level of lean internalisation is high.

Originality/value – This study provides useful information for managers of manufacturing firms by showing the correlation between LT internalisation and Industry 4.0 technologies, corroborating that optimal implementation of these technologies is preceded by a high level of LT internalisation. Furthermore, although there are studies showing the relationship between LTs and Industry 4.0 technologies, none consider the intensity of their implementation.

Keywords Lean tools, Internalisation, Industry 4.0, Survey, Manufacturing industry, Technologies

Paper type Research paper

1. Introduction

In the industrial manufacturing sector, the prime focus lies on addressing wastage issues such as unnecessary transportation, excess inventory, redundant movement or waiting, overproduction, overprocessing and defects, as highlighted in various studies (Bashar *et al.*, 2021; Gottmann *et al.*, 2013; Muthukumaran *et al.*, 2019; Ohno, 1988; White *et al.*, 2015;

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Should data be required, the authors can be contacted via email.

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Womack *et al.*, 1990; Womack and Jones, 1997). To combat these concerns, companies have increasingly embraced lean principles and tools, aiming to curtail waste and thereby enhancing their competitive edge (Belekoukias *et al.*, 2014; Garza-Reyes *et al.*, 2012; Hopp and Spearman, 2021; Saad *et al.*, 2023). Concurrently, the emergence of Industry 4.0 has ushered in a new era of digitalization, promising enhanced production capacity and flexibility within manufacturing systems, giving companies substantial competitive advantage (Brunelli *et al.*, 2017; Dalenogare *et al.*, 2018; Kundu *et al.*, 2021; Meindl *et al.*, 2021; Theorin *et al.*, 2017).

In view of the above, this study aims to test the relationship between lean tools (LTs) and Industry 4.0 technologies (TECH_i4.0s). With regard to internal LTs, our study is based on the model proposed by Shah and Ward (2007), and TECH_i4.0s is underpinned by Brunelli *et al.*'s (2017) "horizontal and vertical system integration" classification, particularly production control technologies. This study also addresses the concept of internalisation, which Allur *et al.* (2014) and Nair and Prajogo (2009), refer to as the daily, active use of tools or technologies in all company areas and processes. Regarding the level of use, companies may be at different stages of adopting LTs or TECH_i4.0s (Cagliano *et al.*, 2019; Marcon *et al.*, 2022; Pacchini *et al.*, 2019; Tortorella *et al.*, 2018).

To our knowledge, there are no studies on the relationship between levels of internalisation of LTs and TECH_i4.0s in European manufacturing companies. We only found studies on the level of internalization of LTs (Losonci and Demeter, 2013; Sahoo and Yadav, 2018). This study therefore bridges this research gap and contributes to the existing literature by analysing the relationship between levels of internalisation of LTs and TECH_i4.0s in European manufacturing companies.

The remainder of the paper is structured as follows. Section 2 reviews previous literature; Section 3 describes the methodology designed to answer the research questions based on data from the survey; the results and discussion are presented in Sections 4 and 5, respectively. Section 6 presents the conclusions, limitations of the study and future lines of research.

2. Overview of research context

This section deals with lean methodology and the implementation of various LTs, followed by a description of Industry 4.0 technological tools and a discussion on the relationship between the two based on the literature examined.

The search strategy involved a literature search to identify the main concepts by selecting library resources and reviewing and refining results. The main concepts used are "Industry 4.0 technologies" and "Lean tools" combined with "internalisation", "survey" and "Manufacturing Industry" in both the title and abstract. The research was conducted in 2022 using Scopus database (obtaining 421 papers) and ResearchGate database (obtaining 307 papers) between 2017 and 2022. Following a snowball method, we eliminated overlaps obtaining finally 62 papers.

2.1 Lean tools

Lean methodology, which originated in the Toyota Production System, helps manufacturing companies improve production and competitiveness (Belekoukias *et al.*, 2014; Dora *et al.*, 2013; Durakovic *et al.*, 2018; Garza-Reyes *et al.*, 2012; Kumar *et al.*, 2018; Netland, 2013; Zahraee *et al.*, 2014) by eliminating waste and reducing cycle time and component costs (Anand and Kodali, 2009; Godinho Filho *et al.*, 2016; Haddud and Khare, 2020; Henrique *et al.*, 2016; Jasti and Sharma, 2015; Mazzocato *et al.*, 2010; Muthukumaran *et al.*, 2019).

Companies introduce this methodology by implementing tools that are either internal or external to the organisation. Internal tools are related to manufacturing processes, equipment, production planning and control and human resource management; external tools, on the other hand, are linked to the relationship companies have with suppliers and customers (Moyano-Fuentes and Sacristán-Díaz, 2012; Olhager and Prajogo, 2012; Salonitis and Tsinopoulos, 2016; Shah and Ward, 2007).

The model proposed by Shah and Ward (2007) is taken as a reference for these internal and external LTs, as it has been widely accepted in previous literature. Internal LTs include Kanban, value stream mapping (VSM), specific lines, visual management, single-minute exchange of die (SMED), 5S, total productive maintenance (TPM), standardised work, Six Sigma, continuous improvement and task integration. The main tools of the external sphere include information exchange between customers and suppliers, on-time delivery of raw materials, the involvement of suppliers in customers' production processes and a focus on the end customer.

Concerning LTs, internal (shop floor) tools were selected from Shah and Ward's (2007) model. This was because it is generally easier to control the internal factors, which are focused on LTs related to internal aspects of organisations; external factors are usually more difficult to control (Losonci and Demeter, 2013). These internal factors relate to manufacturing processes, equipment, production planning and control and human resource management (Moyano-Fuentes and Sacristán-Díaz, 2012; Olhager and Prajogo, 2012; Salonitis and Tsinopoulos, 2016; Shah and Ward, 2007).

However, although lean implementation may be successful at first, many companies are unable to sustain the initial momentum, and the benefits often dissipate in the long term because of the difficulty of maintaining new routines (Netland, 2016; Sartal *et al.*, 2022).

According to Dorval *et al.* (2019) and Mathur *et al.* (2012), these difficulties may be because of an often inherent resistance to new production practices and routines on the part of workers, which makes it difficult for organisations to communicate and transfer lean concepts. Other authors such as Henrique *et al.* (2016) and Hernández-Matias *et al.* (2020) highlight that a lack of commitment to lean implementation on the part of manufacturing directors and managers, together with limited investment in employee training, can lead to failure in lean implementation.

Therefore, valuable information is gained from studying the extent of internalisation as it is often related to the performance of workers and manufacturing managers. For example, many authors mention factors such as commitment and involvement from top management in manufacturing companies, which may affect the degree of LT implementation (Behrouzi and Wong, 2011; Dorval *et al.*, 2019; Durakovic *et al.*, 2018; Netland, 2016; Reda and Dvivedi, 2022; Salonitis and Tsinopoulos, 2016; Tezel *et al.*, 2018; Tortorella *et al.*, 2018) or education and worker engagement and empowerment (Danese *et al.*, 2017; Hernández-Matias *et al.*, 2020; Knol *et al.*, 2018; Losonci *et al.*, 2011; Netland *et al.*, 2015; Netland and Ferdows, 2016; Saini and Singh, 2020; Salonitis and Tsinopoulos, 2016; Shah and Ward, 2007; Sundar *et al.*, 2014).

As Dornelles *et al.* (2022) and Pereira and Sachidananda (2022) point out, the human factor is vital in any advanced manufacturing system, whether in relation to the use of LTs or TECH_i4.0s. In fact, some more recent studies have proposed the concept "Operator 4.0", highlighting the relevance of the human factor in adopting Industry 4.0 technologies (Meindl *et al.*, 2021; Romero *et al.*, 2016).

2.2 Technologies specific to Industry 4.0

Recent developments in traditional supply chains have been facilitated by TECH_i4.0s such as radio frequency identification (RFID), artificial intelligence, blockchain, Internet of

Things (IoT) or sensor technologies that enable direct tracking of commodities in manufacturing sectors, which has led to customised supply chains with higher performance (Ghadge *et al.*, 2020; Halim-Lim *et al.*, 2023).

Furthermore, some technological tools related to Industry 4.0 are designed for the production area (Dabhilkar and Åhlström, 2013; Danese *et al.*, 2017; Shah and Ward, 2007). These tools are aimed at integrating physical production in operations using smart technology, which mainly includes smart factories, cloud computing, IoT, cognitive computing, artificial intelligence, cyber-physical systems and big data (Dornelles *et al.*, 2022; Frank *et al.*, 2019; Marcon *et al.*, 2022; Meindl *et al.*, 2021; Pereira and Sachidananda, 2022; Sousa-Zomer *et al.*, 2020).

Brunelli *et al.* (2017) Ghadge *et al.* (2020) and Subramaniyam *et al.* (2021) point to 9 TECH_i4.0s as a framework of reference: advanced robots (autonomous and cooperative robots), additive manufacturing (construction of objects using 3D models), augmented reality (visualisation using a device with added virtual information), simulation (optimising networks with real-time data from intelligent systems), horizontal and vertical system integration (fully integrated value chain and organisational structure), the industrial IoT (interconnection of devices and objects through a network), cloud computing (management of large volumes of data in open systems), cybersecurity (management of network security risks because of the connection between smart machines, products and systems) and big data and analytics (comprehensive evaluation of available data).

Notably, the main characteristic features of Industry 4.0 are horizontal and vertical collaboration and systems integration. In vertical integration, information and communication technologies are integrated at different organisational levels, from control at shop-floor level to production, operations and management levels. This vertical integration network means that cyber-physical systems can be used to make production more responsive to variations in demand or fluctuations and shortages in levels of stock. In horizontal integration, TECH_i4.0s are used for information exchange between different actors along the supply chain (Ghadge *et al.*, 2020; Subramaniyam *et al.*, 2021).

TECH_i4.0s from the "Horizontal and vertical system integration" group were therefore selected for this study, as they are specific to internal production control in a similar way to the internal LTs selected, in what are known as "shop-floor LTs" and "shop-floor technologies" (Sartal *et al.*, 2017). Furthermore, authors such as Narula *et al.* (2022) and Sartal *et al.* (2022) highlight the productive performance of using in-house LTs and vertical and horizontal data integration technologies jointly, even ahead of other more prevalent TECH_i4.0s in manufacturing workshops such as advanced robotics, additive manufacturing or big data.

2.3 The relationship between lean tools and Industry 4.0 technologies

Cifone *et al.* (2021), Reyes *et al.* (2023), Sartal and Vázquez (2017) and Tortorella *et al.* (2020) point out the need to implement LTs and to make use of new technologies to maintain the dynamics of improvement over time. Feldmeth and Müller (2019), Kumar *et al.* (2023) and Sartal *et al.* (2022) argue that when LTs are used on their own, they have particular weaknesses compared to current structural trends. Rosin *et al.* (2020) add that the lean strategy should be adapted or reconsidered to prioritise the deployment of Industry 4.0 technology.

Ma *et al.* (2017), Pagliosa *et al.* (2021) and Rossini *et al.* (2022) claim that introducing TECH_i4.0s in companies can help lean practices and initiatives improve productivity and process flexibility. Buer *et al.* (2021) go further in their assertions, arguing that integration between TECH_i4.0s and lean practices is essential to achieve superior operational performance and that this competitive advantage virtually disappears when they are used separately.

Brunelli *et al.* (2017), Khanchanapong *et al.* (2014) and Rossini *et al.* (2023) maintain that companies generate synergistic performance by implementing lean management and Industry 4.0 together rather than independently or sequentially. This integrated approach, often referred to as "Lean Industry 4.0", unlocks the potential of Industry 4.0 while achieving higher levels of productivity from LTs, thereby preventing the automation of waste (Brunelli *et al.*, 2017; Küpper *et al.*, 2017; Rossini *et al.*, 2022). However, there is little empirical evidence on the relationships, synergies and trade-offs between lean management practices and TECH_i4.0s (Buer *et al.*, 2018; Haddud and Khare, 2020; Sartal *et al.*, 2022), and it remains unclear which technologies can be combined with current lean practices, which complement each other and which may be counterproductive (Åhlström *et al.*, 2021; Rossini *et al.*, 2023; Sartal *et al.*, 2022; Wagner *et al.*, 2017).

The order of implementation is also unclear. Bittencourt *et al.* (2019), Brunelli *et al.* (2017), Buer *et al.* (2021), Ding *et al.* (2023) and Rahardjo *et al.* (2023) propose first carrying out lean implementation to generate efficient processes from the outset, and then adding TECH_i4.0s to these processes to maximise performance. Sartal and Vázquez (2017) support this theory by arguing that excessive, early adoption of new technologies linked to LTs may represent investments with low returns.

Recent studies on the use of LTs and TECH_i4.0s with industrial performance include Lalic *et al.* (2019), Marinelli *et al.* (2021), Narula *et al.* (2022), Sartal *et al.* (2017), Sartal *et al.* (2022), Tortorella *et al.* (2019) and Tortorella *et al.* (2021).

Other scholars such as Ojha (2023), Pereira and Sachidananda (2022) and Sanders *et al.* (2016) argue that combining lean manufacturing and smart manufacturing technology has the potential to increase productivity and reduce waste. Gong *et al.* (2019) and Wang *et al.* (2017) also point out that Industry 4.0 acts as a supporting factor for the implementation of LTs in organisations. Another study by Lalic *et al.* (2019) shows a positive correlation between tools specific to lean "organisational concepts" and Industry 4.0 technology tools. Furthermore, Lacerda *et al.* (2016) and Wong *et al.* (2014) conclude that combining lean-type organisational concepts and technology-type tools leads to operational improvements.

Based on all of the above, the following research question is formulated:

RQ1. Is there a correlation between LT internalisation levels and Industry 4.0 technologies in European manufacturing companies?

Technological advances in recent years have enabled companies to become increasingly competitive and efficient. For example, the enterprise resource planning (ERP) technology tool and its application in manufacturing companies using LTs has generated significant synergies, enabling increased efficiency and competitiveness (Iris and Cebeci, 2014; Liutkevičienė *et al.*, 2022; Zhang *et al.*, 2005). These ERP systems enable companies to automate and integrate most of their business processes, share common data and practices across the business, produce and access information in a real-time environment (Alaskari *et al.*, 2013; Forsman *et al.*, 2012), as well as determining whether objectives are satisfactorily achieved over time (Saniuk and Waszkowski, 2016).

Rafique *et al.* (2016) and Sartal *et al.* (2022) argue that connecting data at the same level through technologies such as Wi-Fi or RFID helps to successfully meet the growing demands of Just-in-Time (JIT) systems. Furthermore, Sanders *et al.* (2016) state that the connection between manufacturing execution systems (MES) and ERP enables manufacturers to achieve higher levels of performance. Jardini *et al.* (2016) and Sartal *et al.* (2022) also point out that using electronic data interchange (EDI) systems facilitates visibility and improves deliveries in JIT systems throughout the supply chain. This underpins the second research question:

RQ2. Which Industry 4.0 technologies are most dependent on the use of LTs in European manufacturing companies?

3. Materials and methods

This section describes the methodology used to answer the research questions posed in the present study.

3.1 Sample

The data for the study were drawn from the European Manufacturing Survey (EMS), coordinated by the Fraunhofer Institute for Systems and Innovation Research in Karlsruhe, Germany. The EMS aims to standardise information on organisational and technological issues related to European manufacturing companies. Manufacturing companies from Spain, Austria, Sweden, Lithuania, Slovakia, Croatia, Serbia and Slovenia participated in this study. Eligibility to be surveyed included having a Nomenclature of Economic Activities (NACE) Code 10–33 corresponding to the manufacturing sector, and more than 20 employees (see Table 1).

The data used for the purpose of the present study were collected using the EMS 2018 edition, consisting of 1,298 surveys carried out in Austria, Croatia, Lithuania, Serbia, Slovakia, Slovenia, Spain and Sweden. The mailing was followed up by a phone call after one week. In addition to the initial email, two further follow-up emails were sent after one month and three months. The survey responses were collected at the end of the process.

No. Employees	Small 1–50	491	37.83%
	Medium 51–250	468	36.06%
	Large >250	223	17.18%
	N/A	116	8.94%
	Total	*1,298*	*100.00%*
Sector (NACE code)	Agri-food (10–12)	102	7.86%
	Textile (13–15)	60	4.62%
	Chemical (20–21)	28	2.16%
	Electronics (26–28)	166	12.79%
	Automotive (29–30)	29	2.23%
	Industrial equipment (16–19, 22–25, 31–33)	414	31.90%
	N/A	499	38.44%
	Total	*1,298*	*100.00%*
Country	Austria	253	19.5%
	Croatia	105	8.1%
	Lithuania	199	15.3%
	Serbia	240	18.5%
	Slovakia	114	8.8%
	Slovenia	127	9.8%
	Sweden	175	13.5%
	Spain	85	6.5%
	Total	*1,298*	*100.00%*

Source: Authors' own creation

Table 1. Distribution of responses according to company size, sector and country

Table 1 shows the distribution of the data collected according to company size, production sector and country.

Regarding the validation of the questionnaire, the EMS consortium has established several procedures to avoid problems arising from language differences and the specific terminology used by respondents: for example, pilot testing in different countries and back-translation methods. These procedures facilitate international comparisons and enable the results to be generalized. Data from the eight selected countries could therefore be merged, as the questions and criteria used for sample selection were the same (Bikfalvi *et al.*, 2014).

The survey was conducted by making random phone calls to manufacturing plants, some of which went unanswered. In these cases, no specific call pattern was evident, nor were reasons given for not responding. Therefore, there is no evidence that responses were received only from one particular type of firm, so it was deemed unnecessary to take into account the non-response bias that may have occurred in the regular mail surveys.

A comparison of early and late responses found no statistically significant differences in any of the study variables. Furthermore, additional statistical tests were conducted to ensure the feasibility of merging data from all countries studied. For more details on this survey, please refer to previous publications related to the EMS (Barón Dorado *et al.*, 2022; Lalic *et al.*, 2019; Palacios Gazules *et al.*, 2023; Sartal *et al.*, 2022).

Regarding the profile of respondents, we selected top-level respondents such as manufacturing managers, industrial managers and CEOs with a clear global perspective or access to information on industrial and commercial requirements, as these tend to be more reliable sources of information than lower-level management (Sartal *et al.*, 2017).

3.2 Variables and encodings

Two types of variables were used in the research: primary data, obtained directly from the answers to the questions asked in the survey, and derived data, which were generated through specific calculations based on the primary data, as seen in "Formula 1". This process allowed us to deepen the analysis by assessing the relevant correlations between LTs and TECH_i4.0s. For our research and corresponding survey, we selected LTs relative to the companies' internal processes. These tools were "Standardised work", "VSM", "SMED", "Visual management" and "TPM", grouped under the name LTs.

Regarding TECH_i4.0s, technologies in line with the "Horizontal and vertical system integration" classification were chosen, particularly those related to production control.

Vertical integration groups technological systems at different hierarchical levels of production and factory management. Horizontal integration corresponds to the exchange of real-time information and resources between companies (Dalenogare *et al.*, 2018).

The survey describes these as "mobile devices", "digital solutions", "ERP", "EDI", "MES", "RFID", "product life cycle" and "virtual reality", henceforth grouped under the name "TECH_i4.0s". Table 2 describes the LTs and TECH_i4.0s used in this study.

First, a descriptive statistical study was carried out using SPSS software. Two variables were used to answer the questions about LTs and TECH_i4.0s use: the use or non-use (yes or no) and the level of internalisation (LI) (1, 2 or 3). Regarding LI, Level 1 means low use of LTs or TECH_i4.0s, Level 2 means medium use of LTs or TECH_i4.0s and Level 3 means high use of LTs or TECH_i4.0s. Regarding measuring the internalisation variables, companies were asked a direct question, as indicated in earlier studies (e.g. Naveh and Marcus, 2005), about the active and daily use of LTs and TECH_i4.0s in all areas and processes of the companies (Allur *et al.*, 2014; Nair and Prajogo, 2009).

Lean tools (LTs)	Questions in the survey (No = "0"; yes = "1"; non sense = "–") Which of the following organisational concepts are currently used in your factory?
Standardised work	Standardised and detailed work instructions (e.g. standard operation procedures SOP, MOST) – standardised work
VSM	Measures to improve internal logistics (e.g. value stream mapping/design, changed spatial arrangements of production steps) – VSM
SMED	Fixed process flows to reduce setup time or optimize change over time (e.g. SMED, QCO) – SMED
Visual management	Display boards in production to illustrate work processes and work status (e.g. visual management)
TPM	Methods of assuring quality in production (e.g. CIP, TQM, preventive maintenance) – TPM
Technologies 4.0 (TECH_i4.0s)	*Questions in the survey (No = "0"; yes = "1"; non sense = "–") Which of the following production control technologies are currently used in your factory?*
Mobile devices	Mobile/wireless devices for programming, controlling or monitoring machinery (e.g. Tablets)
Digital solutions	Digital solutions for supplying drawings, work calendars or work instructions directly to the production floor
ERP	Enterprise resource planning (ERP) software
EDI	Exchange of production schedules with suppliers/customers (electronic data interchange)
MES	Real-time production control system (e.g. centralized operations and data acquisition system, MES)
RFID	System for the automation and management of internal logistics (e.g. warehouse management system, RFID)
Product life cycle	Product life cycle management
Virtual reality	Virtual reality or simulation for product design and development (e.g. FEM, digital prototypes, computer models)

Source: Author's own creation

Table 2. Description of lean tools and Industry 4.0 technologies

Another possible answer to the survey questions could be "N/A", in the case that using LTs or TECH_i4.0s did not make sense in their organization.

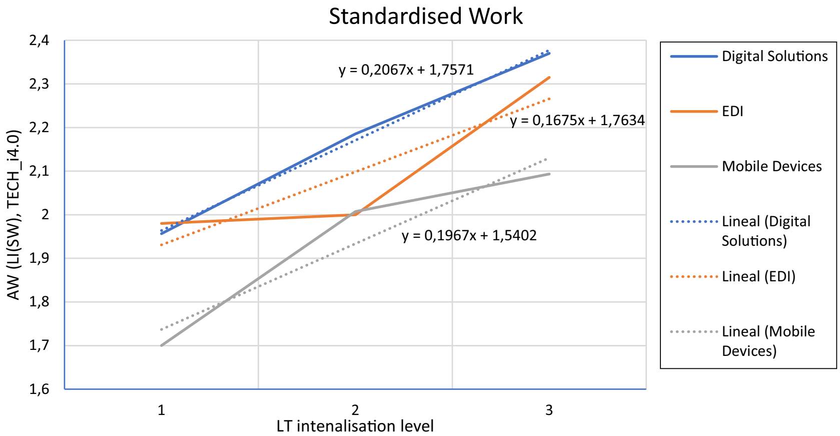
New derived data were extracted from the survey variables to calculate the following: LI of LTs [LI (LTs), Level of Internalization of the Lean Tools, LTs], LI of TECH_i4.0s [LI (TECH_i4.0s), Level of Internalization of Industry 4.0 Technologies, TECH_i4.0s]. The name of the secondary variable is WA (weighted average) of LTs and TECH_i4.0s, as shown in Formula 1:

$$\text{WA}\,(\text{LTs},\ \text{TECH\_i4.0s}) = \text{SUM}\,\text{j} = 0.3\,\{\%\,\text{Firms}\,(\text{LI}\,(\text{TECH\_i4.0s}) = \text{j})*\text{j}\} \quad (1)$$

for each LI (LTs) = 0.3 and each LI (TECH_i4.0s) = 0.3

To illustrate the model developed, Figure 1 shows an example of the linear relationships between TECH_i4.0s "digital solutions", "EDI" and "mobile devices" and "standardised work" in relation to LTs.

Developing the model involved examining the relationship between LTs and TECH_i4.0s variables using correlation and linear regression. Although linear regression is a good measure of causality, and several scholars affirm this correlation, it is still not clear in the literature whether this type of relationship exists between these two variables (Lalic *et al.*, 2019; Narula *et al.*, 2022; Sartal *et al.*, 2022).



Source: Authors' own creation

Figure 1. Example of linear relationship between selected TECH_i4.0 and the standardised work LT

4. Results

The results of the study are presented in Tables 3–7. Table 3 shows the findings from the descriptive analysis of the primary data variables. The missing data (N/A) are also shown in the table. The average represents the number of companies that have implemented LTs and TECH_i4.0s. Findings show that the use of LTs tools is higher (54.4%) than TECH_i4.0s (34.8%) in the companies surveyed (see Table 3), which indicates a greater presence and importance of LTs in the production systems of the manufacturing companies surveyed compared to TECH_i4.0s. Moreover, the LT is worth noting is "standardised work" (71.2%) and about TECH_i4.0s is "ERP" (58.6%).

Table 3. Primary data from EMS survey: number of firms in the implementation of LTs and TECH_i4.0s and levels of internalisation in firms where tool or tech is implemented

	Implementation (Y/N)			Internalisation level (1, 2 or 3)			
	*Yes**	*No*	*N/A*	*LI1*	*LI2*	*LI3*	*N/A**
LTs							
Standardised work	924 (71.2%)	297	77	139	398	387	0 (0.0%)
VSM	622 (47.9%)	578	98	138	343	141	0 (0.0%)
SMED	566 (43.6%)	636	96	112	268	150	36 (6.4%)
Visual management	632 (48.7%)	568	98	95	274	224	39 (6.2%)
TPM	788 (60.7%)	415	95	121	296	326	45 (5.7%)
Average	*54.4%*						*3.6%*
TECH_i4.0s							
Mobile devices	403 (31.0%)	783	112	87	185	100	31 (7.7%)
Digital solutions	558 (43.0%)	626	114	92	208	213	45 (8.1%)
ERP	760 (58.6%)	431	107	51	239	405	65 (8.6%)
EDI	586 (45.1%)	619	93	94	226	161	105 (17.9%)
MES	480 (37.0%)	717	101	70	179	150	81 (16.9%)
RFID	330 (25.4%)	855	113	64	127	102	37 (11.2%)
Product life cycle	206 (15.9%)	786	306	50	85	52	19 (9.2%)
Virtual reality	290 (22.3%)	887	121	66	107	96	21 (7.2%)
Average	*34.8%*						*10.8%*

Note: *It also appears percentages of LTs and TECH_i4.0s used and percentages of missing values in internalisation
Source: Authors' own creation

	Mobile devices	Digital solutions	ERP	EDI	MES	RFID	Product life cycle	Virtual reality
Standardised work								
1	1.70	1.96	2.33	1.98	1.88	1.76	1.53	1.70
2	2.01	2.19	2.43	2.00	2.10	1.94	1.84	2.02
3	2.09	2.37	2.63	2.31	2.36	2.33	2.17	2.28
VSM								
1	1.85	1.88	2.33	1.98	2.05	1.73	1.30	1.93
2	1.96	2.31	2.50	2.15	2.13	2.03	1.88	2.02
3	2.15	2.52	2.82	2.31	2.47	2.43	2.36	2.25
SMED								
1	1.82	1.89	2.31	1.83	1.83	1.52	1.38	1.81
2	1.93	2.25	2.50	2.27	2.14	2.06	2.05	2.08
3	2.19	2.43	2.68	2.29	2.50	2.49	2.21	2.57
Visual management								
1	1.77	1.84	2.24	1.92	2.05	2.04	1.67	1.68
2	1.98	2.18	2.52	2.18	2.13	2.01	1.86	2.20
3	2.14	2.38	2.68	2.29	2.38	2.20	2.06	2.28
TPM								
1	1.57	1.97	2.27	1.80	1.81	1.58	1.38	1.62
2	1.94	2.11	2.42	2.05	2.09	1.84	1.91	1.99
3	2.18	2.45	2.72	2.36	2.44	2.37	2.18	2.39

Source: Authors' own creation

Table 4. Results of derived data WA (LTs, TECH_i4.0s)

Correlations	Mobile devices	Digital solutions	ERP	EDI	MES	RFID	Product life cycle	Virtual reality
Standardised work	0.951	0.998	0.986	0.891	0.999	0.978	1.000	0.998
VSM	0.985	0.982	0.986	1.000	0.945	0.997	0.998	0.971
SMED	0.977	0.984	1.000	0.890	0.999	0.998	0.941	0.987
Visual management	0.997	0.991	0.986	0.973	0.961	0.796	1.000	0.920
TPM	0.992	0.970	0.981	0.998	0.997	0.981	0.983	1.000

Source: Authors' own creation

Table 5. Correlations between LTs and TECH_i4.0s based on derived data

Gradient	Mobile devices	Digital solutions	ERP	EDI	MES	RFID	Product life cycle	Virtual reality
Standardised work	0.197	0.207*	0.150	0.167	0.243*	0.283	0.321*	0.291*
VSM	0.147	0.321	0.246	0.161*	0.212	0.350	0.532*	0.159
SMED	0.186	0.270	0.185*	0.232	0.337*	0.488*	0.412	0.382
Visual management	0.186*	0.270	0.217	0.187	0.162	0.083	0.197*	0.298
TPM	0.309	0.238	0.221	0.279*	0.314*	0.397	0.400	0.386*

Note: *means p_value <0.05
Source: Authors' own creation

Table 6. Calculation of the gradient between LTs and TECH_i4.0s

Table 4 shows the results of the derived data and compares the LI of LTs and the LI of TECH_i4.0s. In all the cases studied, the higher the LI of LTs, the higher the value of the derived data WA (LTs, TECH_i4.0s). The following results were obtained from the distribution of firms according to the LI of LTs and the LI of TECH_i4.0s in Appendix.

This indicates that the companies analysed tend to internalise more TECH_i4.0s if they had a high LI of LTs previously. In practice, this result seems to indicate that prior adoption of LTs as an organisational basis in production systems facilitates a more effective implementation of TECH_i4.0s. Furthermore, we observed a close relationship between TECH_i4.0 "ERP" and all LTs, which is always higher than 2. This result suggests that TECH_i4.0 "ERP" has a high level of implementation regardless of the LI of the LTs.

A correlation study was carried out using the derived data to test the relationship between LTs and TECH_4.0. This revealed that all combinations were very highly correlated, with an average value of 0.974. The results are set out in Table 5.

The results of the correlation analysis show no correlation that can be justified by previous literature. However, Figure 1 shows a tendency towards a relationship between LTs and TECH_i4.0s.

Nevertheless, one way to quantify this relationship is to perform a linear regression using the derived data. The results of these linear regressions are the cut-off point and gradient, indicators that explain the relationship between each LTs and TECH_i4.0s beyond a simple correlation.

This shows which LTs tend to increase internalisation of TECH_i4.0s use. The cut-off point, on the other hand, is used to analyse the degree of dependence between the use of LTs and TECH_i4.0s and examine whether TECH_i4.0s use depends to a greater or lesser extent on prior LT implementation.

A correlation table was used to answer *RQ1* (Table 5), and the gradient between the variables was calculated to better explain their relationships beyond this correlation.

The indicators marking LTs behaviour with respect to TECH_i4.0s were the cut-off point and gradient.

Results in Table 5 showed a positive outcome for the first research question (*RQ1*), which analysed whether there was a relationship between the LI of LTs and TECH_i4.0s in European manufacturing companies, as all correlations were positive.

Table 6 shows individual results for the gradient between LTs and TECH_i4.0s relationship and which of them have statistical significance (p_value < 0.05). We observed that TECH_i4.0 "MES" and "Product life cycle" are significantly related to more LTs, with a total of 3 LTs each. This result, in practice, indicates that the implementation of TECH_i4.0 "MES" is favoured by previous use of Shop Floor LTs, such as "Standardised Work", "SMED" and "TPM".

The second research question (*RQ2*), which analysed the dependency relationship between TECH_i4.0s and LTs in European manufacturing companies, was answered using cut-off point and gradient results.

Table 7. Calculation of the cut-off point between LTs and TECH_i4.0s

Cut-off point	Mobile devices	Digital solutions	ERP	EDI	MES	RFID	Product life cycle	Virtual reality
Standardised work	1.540	1.757*	2.163*	1.763	1.626*	1.447	1.204*	1.419*
VSM	1.692*	1.593	2.055*	1.824*	1.792	1.366*	0.786	1.749*
SMED	1.608*	1.649*	2.127*	1.667	1.480*	1.046*	1.058	1.389
Visual management	1.593*	1.594*	2.046*	1.757*	1.862*	1.918*	1.470*	1.454
TPM	1.280*	1.699	2.028*	1.514*	1.486*	1.136	1.024	1.225*

Note: *means p_value <0.05
Source: Authors' own creation

Additionally, regarding the cut-off point, adoption of TECH_i4.0 “ERP” is the most independent with respect to LTs adoption in European manufacturing companies (see Table 7) because all values are higher than 2 with statistical significance for all LTs, which shows that this TECH_i4.0 can be implemented prior to LTs use.

5. Discussion

Regarding the first research question (*RQ1*), it should be noted that all relationships between LTs and TECH_i4.0s show a high, positive correlation, indicating a strong relationship between them, as shown in Table 5. The answer to the first research question (*RQ1*) is therefore affirmative. This relationship is also illustrated in Figure 1, which shows the results of the LI of three of the TECH_i4.0s studied in relation to LT “Standardised work”. All three functions show a similar positive gradient. These results show growing internalisation between LTs and TECH_i4.0s.

Table 6 does not show a common pattern in relationships between LTs and TECH_i4.0s, but in the results, there is a statistical significance, we could not reject the correlation.

Thus, companies should promote internal LTs to achieve better implementation, especially for the highlighted TECH_i4.0s.

Table 5 shows that LI of all the LTs positively affects the LI of TECH_i4.0s. Thus, it can be stated that a higher implementation of LTs induces a higher engagement with TECH_i4.0s. Therefore, it is recommended that managers of manufacturing companies implement LTs on an organizational basis first, so to then obtain productive synergies with the adoption of TECH_i4.0s.

With regard to the second research question (*RQ2*), Table 7 shows that TECH_i4.0 “ERP” depends the least on LTs, followed by “Mobile Devices” and “MES”. This suggests that adopting these TECH_i4.0s does not require implementing internal LTs beforehand. In fact, according to the cut-off point results, “ERP” almost always has values higher than 2 compared to LTs, demonstrating that it is less dependent on LTs than the other TECH_i4.0s.

As it may take some time to implement LTs, another practical implication that can be recommended to managers of manufacturing companies is to take advantage of the potential offered by TECH_i4.0s, particularly “ERP” technology. As the findings of our study prove, this TECH_i4.0 can be implemented independently of LTs from the beginning. In this way, manufacturing companies could benefit from the competitive advantages offered by this technology from early stages, such as reduced production costs and increased productivity, without the need to use LTs simultaneously. Later, when the implementation of LTs is completed, important productive synergies could be established with “ERP” by taking advantage of the organizational improvements offered by the Lean methodology through its tools.

The results of this study are in line with findings from previous literature, in that the companies analysed use more TECH_i4.0s if they have prior, high LTs usage (Narula *et al.*, 2022; Sartal *et al.*, 2017; Tortorella *et al.*, 2019). Some authors even mention that using TECH_i4.0s from the “horizontal and vertical integration system” group is closely related to using internal LTs. (Narula *et al.*, 2022; Sartal *et al.*, 2022).

In particular, Saad *et al.* (2023), Buer *et al.* (2018) and Sanders *et al.* (2016) argued that joint use of “ERP” and “MES” technologies offers an optimised flow of operations, in line with lean methodology objectives and high performance in companies. Jardini *et al.* (2016) and Sartal *et al.* (2022) point out the relationship between TECH_i4.0 “EDI” with LTs.

Research by authors such as Sartal *et al.* (2017) or Szász *et al.* (2021) focuses on identifying significant relationships between groups of latent variables. In contrast, in our contribution, we were comparing variables individually by correlations and linear regressions to observe the behaviour of each TECH_i4.0s in relation to LTs. In fact, some authors such as Iris and Cebeci (2014) and Zhang *et al.* (2005) argue that using "ERP" technologies is related to the use of LTs. This has been verified in our study, which demonstrates that "ERP" has an internalisation relationship with some of the LTs analysed. However, as mentioned previously, "ERP" is the most independent TECH_i4.0 regarding LTs implementation. This means that although it is closely related to lean, it can be implemented independently in companies without the initial support of lean methodology.

Furthermore, given the impact of workers on the improvements in levels of internalisation and based on the results obtained, it is suggested that training programmes should encompass specific modules on the practical implementation of lean methodology and the application of TECH_i4.0s. It is of utmost importance to highlight the success stories mentioned in the literature, along with strategies aimed at overcoming common barriers.

Additionally, it is advised to prioritise TECH_i4.0s, as we observed certain interactions with LTs that were previously implemented. For example, initially implementing ERP systems, which are the most independent technology in environments that have already applied lean, would facilitate the successive introduction of other TECH_i4.0s. By centralising information and processes, the organisation is prepared to take advantage of new technologies.

6. Conclusions

We conclude that the companies analysed tend to internalise more TECH_i4.0s if they already have a high LI of LTs, as reflected in the results. Therefore, appropriate implementation of LTs should be the first priority before integrating TECH_i4.0s.

The results show that TECH_i4.0 "ERP" is the most independent from LTs according to its LI. "Mobile Devices" and "MES" also show significant values for LTs independence. This indicates that, to a large extent, these TECH_i4.0s do not require the support of LTs to be implemented in companies.

The originality of our contribution lies in the fact that it analyses the level of internalisation of LTs and TECH_i4.0s as a whole. Although some current research shows the relationship between LTs and TECH_i4.0s, none of these studies consider the intensity of implementation.

Regarding the limitations of this study, we focused exclusively on European countries, even though many emerging economies have begun to implement TECH_4.0s. However, it is uncertain whether the results achieved in this contribution can be extrapolated to these situations. Furthermore, the lack of data since we had so many missing data to the survey responses has limited the conclusions of the study. It is also clear that determining the LI by companies of TECH_i4.0s is more complicated than determining the LI of LTs (Table 3). We suspect that LTs are more mature tools than the application of new digital technologies. However, we believe that results indicate a strong relationship between LTs and TECH_i4.0s.

Lean methodology has been practised for over 30 years; however, the Industry 4.0 paradigm is more recent and constantly evolving. Future research could relate the LTs studied with the other 8 TECH_i4.0s in the literature previously mentioned. The most suitable technologies for further study could be those used in operational and production processes such as advanced robots, additive manufacturing, augmented reality and simulation, to evaluate their relationship with LTs implementation.

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Appendix

	Mobile devices				MES		
	1	*2*	*3*		*1*	*2*	*3*
1	13	13	4	*1*	13	10	9
2	37	61	38	*2*	31	72	46
3	26	84	40	*3*	16	76	77
	Digital solutions				*RFID*		
	1	*2*	*3*		*1*	*2*	*3*
1	16	16	14	*1*	8	5	4
2	36	82	71	*2*	30	54	24
3	23	80	97	*3*	17	57	62
	ERP				*Product life cycle*		
	1	*2*	*3*		*1*	*2*	*3*
1	10	23	31	*1*	10	5	2
2	18	105	126	*2*	23	32	12
3	11	79	182	*3*	15	43	30
	EDI				*Virtual reality*		
	1	*2*	*3*		*1*	*2*	*3*
1	13	25	12	*1*	11	4	5
2	36	82	36	*2*	26	40	28
3	22	80	79	*3*	17	50	50

Source: Authors' own creation

Table A1. Standardised work and TECH_i4.0s

	Mobile devices				MES		
	1	*2*	*3*		*1*	*2*	*3*
1	14	19	8	*1*	12	17	14
2	35	71	29	*2*	27	78	47
3	14	30	24	*3*	5	27	38
	Digital solutions				*RFID*		
	1	*2*	*3*		*1*	*2*	*3*
1	25	24	17	*1*	13	12	5
2	25	72	79	*2*	29	60	33
3	7	30	55	*3*	9	16	35
	ERP				*Product life cycle*		
	1	*2*	*3*		*1*	*2*	*3*
1	11	36	39	*1*	15	4	1
2	20	82	142	*2*	23	41	14
3	2	16	92	*3*	4	20	20
	EDI				*Virtual reality*		
	1	*2*	*3*		*1*	*2*	*3*
1	18	24	17	*1*	12	7	10
2	31	73	55	*2*	22	42	24
3	9	32	31	*3*	9	21	22

Source: Authors' own creation

Table A2. VSM and TECH_i4.0s

	Mobile devices				MES		
	1	*2*	*3*		*1*	*2*	*3*
1	17	18	9	*1*	18	18	10
2	27	59	20	*2*	21	66	38
3	8	39	21	*3*	6	31	49
	Digital solutions				*RFID*		
	1	*2*	*3*		*1*	*2*	*3*
1	21	29	14	*1*	18	10	3
2	24	56	58	*2*	23	53	29
3	6	37	43	*3*	4	22	33
	ERP				*Product life cycle*		
	1	*2*	*3*		*1*	*2*	*3*
1	14	32	41	*1*	17	8	1
2	15	68	114	*2*	14	26	17
3	3	31	82	*3*	6	26	16
	EDI				*Virtual reality*		
	1	*2*	*3*		*1*	*2*	*3*
1	20	29	10	*1*	11	9	6
2	16	58	49	*2*	21	38	28
3	12	31	35	*3*	1	16	25

Source: Authors' own creation

Table A3. SMED and TECH_i4.0s

	Mobile devices				MES		
	1	*2*	*3*		*1*	*2*	*3*
1	16	11	8	*1*	11	15	13
2	24	65	22	*2*	21	69	38
3	22	45	37	*3*	14	45	58
	Digital solutions				*RFID*		
	1	*2*	*3*		*1*	*2*	*3*
1	21	17	13	*1*	7	12	8
2	24	74	50	*2*	25	43	26
3	18	46	69	*3*	18	31	35
	ERP				*Product life cycle*		
	1	*2*	*3*		*1*	*2*	*3*
1	14	22	30	*1*	5	2	2
2	12	72	117	*2*	22	31	13
3	7	40	120	*3*	15	33	19
	EDI				*Virtual reality*		
	1	*2*	*3*		*1*	*2*	*3*
1	14	25	10	*1*	14	9	5
2	20	63	43	*2*	16	29	31
3	18	39	49	*3*	12	26	31

Source: Authors' own creation

Table A4. Visual management and TECH_i4.0s

	Mobile devices				MES		
	1	*2*	*3*		*1*	*2*	*3*
1	25	16	5	*1*	18	15	10
2	28	56	22	*2*	21	64	31
3	21	70	46	*3*	13	60	81
	Digital solutions				*RFID*		
	1	*2*	*3*		*1*	*2*	*3*
1	22	28	20	*1*	11	5	3
2	35	66	51	*2*	38	47	21
3	13	68	89	*3*	9	49	49
	ERP				*Product life cycle*		
	1	*2*	*3*		*1*	*2*	*3*
1	14	33	37	*1*	13	8	0
2	21	76	106	*2*	23	27	17
3	5	56	171	*3*	12	39	26
	EDI				*Virtual reality*		
	1	*2*	*3*		*1*	*2*	*3*
1	21	25	10	*1*	14	8	4
2	32	70	39	*2*	27	35	26
3	16	67	72	*3*	13	34	51

Source: Authors' own creation

Table A5. TPM and TECH_i4.0s

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