Lean and Industry 4.0: Mapping determinants and barriers from a social, environmental, and operational perspective

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Abstract
Manufacturing companies have started to embrace Industry 4.0 and lean principles to stay competitive. However, the real industry implementation of the integrated approach has been challenging. Even separately, both Lean and Industry 4.0 have high failure rates. Understanding these implementations is essential to increase the application's success and build a bridge between academia and industry. This research uses a systematic literature review methodology to identify case studies that integrate the implementation of lean principles with Industry 4.0 technology. The benefits, barriers, and success factors of the integration were investigated, focusing on environmental, social, and operational perspectives. Forty-two case studies that included lean principles and Industry 4.0 technology in the manufacturing context were identified. The integration resulted in various operational benefits regarding lead-time, throughput, and quality. In terms of environmental impact, there is a potential to estimate the use of resources involved in the production and reduce CO_2 emissions. Other benefits include improved employee welfare, better communication, employee empowerment. The main barrier is the investment cost followed by technological readiness. It has been concluded that Lean and Industry 4.0 present considerable potential. However, the integration needs proper understanding on how to start, where to aim, what to be aware of.

Keywords: Lean; Industry 4.0; sustainability; critical success factors

1 Introduction

Lean is one of the most popular management philosophies that aim to reduce costs and increase efficiency. The introduction of Industry 4.0 and its integration with Lean has introduced the hybrid term 'Lean 4.0' (Mayr *et al.*, 2018). Over the last decade, there has been increasing interest in Lean 4.0's potential benefits. Questions have been raised in academia to understand whether integration is synergetic and to identify the correct order of application, but answers to these questions have not been conclusive (Pagliosa, Tortorella and Ferreira, 2019; Rossini, Costa, Tortorella *et al.*, 2019). Nonetheless, interest in the topic has increased over time, as the combined implementation of Lean and Industry 4.0 presents a significant opportunity to reinforce the operational benefits, such as reduced costs, improved efficiency, and added value (Buer *et al.*, 2020; Tortorella *et al.*, 2021). In Germany, Industry 4.0's implementation alone was estimated to lead to a production and resource efficiency of 18% and an economy worth €30M per year (Geissbauer *et al.*, 2014). Further, implementation of Lean and Industry 4.0 together is expected to lead to a cost reduction of 40% within 5 to 10 years of application (Küpper *et al.*, 2017).

However, these benefits are hard to achieve. Even individual implementation of Lean and Industry 4.0 is challenging, and the integrated implementation is even more so. For Industry 4.0, a survey including over 1,000 manufacturing companies showed that only 14% of smart manufacturing initiatives were successful in 2019 (Petit, Brosset and Bagnon, 2019). For Lean, a failure rate of 60-90% has been observed over the years (Pearce, Pons and Neitzert, 2018, Dora, Kumar, Van Goubergen, Molnar, Gellynck, 2013, Dora & Gellynck, 2015). Nonetheless, despite the failure rate, surveys show that digitalisation and continuous improvement implementation rates are rising. For example, in early 2021, a global survey by PwC illustrated that 49% of CEOs aim to increase their investment in smart manufacturing initiatives despite the risk of failure and the economic downturn caused by the Covid-19 pandemic (Boswell *et al.*, 2021).

To improve the future success rate of Lean and Industry 4.0 and enable the efficient use of resources, academia and industry have been striving to understand the determinants such as benefits and success factors behind the integrated and individual implementations of Lean and Industry 4.0. Success factors and barriers allow possible enablers and hindrances to be analysed respectively (Kurpjuweit *et al.*, 2019; Calabrese, Dora, Levialdi Ghiron, Tiburzi, 2020; Dora, et al, 2020). Companies can improve their success rate through prior preparation by considering the success factors and overcoming the barriers. Indeed, several papers have emphasized that without the recognition of barriers and success factors, there is little chance of initiatives being successful (Antony *et al.*, 2012). Similarly, benefits offer an important incentive for companies to support initiatives, which increases the success of the application (Worley and Doolen, 2006; Dora, Kumar, Gellynck, 2016). Hence, identification of the benefits, success factors, and barriers is essential for project success, as it allows companies to prepare effectively for project implementation.

Many studies have been conducted that investigate Lean and Industry 4.0 individually to analyse the determinants behind the application (Jadhav, Mantha and Rane, 2014; Netland, 2016; Orzes et al., 2019; Moeuf et al., 2020a). However, there is limited research on analysing the integration of Lean and Industry 4.0 in practical cases. The available practical case studies on the integrated application are scarce and mostly focus on economic aspects rather than social and environmental dimensions and their combined effect (de Sousa Jabbour et al., 2018a). Furthermore, there is extensive research on the individual benefits, barriers, and critical success factors (CSFs) of Lean and Industry 4.0 in different settings. Hence, there is a need to focus on the synergistic applications of Lean and Industry 4.0. Recent studies have indicated the benefit of the integrated approach, but questions have been raised regarding the key challenges organisations face when managing the integration and the critical factors to overcome the barrier (Buer et al., 2020; Tortorella et al., 2021). The CSFs are key to managing the effective implementation of the integrated approach.

To have a complete assessment, all economic, social, and environmental dimensions and their integration need to be analysed, which can be explained with the help of the triple bottom line

(TBL) principle introduced in the late 1990s. TBL emphasizes that economic, social, and environmental aspects are interrelated and need to be considered to measure a company's performance (Elkington, 1994; Fauzi, Svensson and Rahman, 2010). Analysing only economic aspects, such as cost results, gives only an incomplete assessment, even for assessing long-term economic performance, as the effects of people or the surroundings behind the effect can contribute to a company's performance and development (Carter and Rogers, 2008). Hence, the TBL approach is used in this study, where the benefits, barriers, and success factors are analysed in three dimensions.

This study aims to investigate how the combination of Lean practices with Industry 4.0 tools impacts on the TBL by analysing case studies through the use of a systematic literature review. The goal of the study is to illustrate the benefits, barriers, and CSFs focusing on social, environmental, and economic aspects to understand fully the depths of the integration. In the context of this paper focusing on manufacturing, TBL's economic aspects relate and refer to change in operational performance. Hence, we substituted economic aspect with operational performance in this research.

To the best of our knowledge, this is the first literature review that analyses practical case studies integrating Lean and Industry 4.0 and Lean 4.0 in real manufacturing plants. This contributes to the literature in terms of introducing the benefits, barriers, and CFSs of Lean 4.0 in practical settings. Through incorporating operational, social and environmental aspects, it fills a gap in the literature on the environmental and social dimensions as well as expanding the knowledge on the operational aspect. The interrelation of these three aspects is also included in this review according to TBL. In addition, this study contributes to the literature by analysing the order of application of Lean and Industry 4.0 in case studies. The following research questions will be answered through the analysis of case studies:

RQ.1. *Benefits* – What are the benefits of integrating lean manufacturing principles and Industry 4.0 from the operational, social, and environmental perspectives?
RQ.2. *Success Factors* - What social, environmental, and operational factors have contributed to the success of these case studies?
RQ.3. *Barriers* - What are the social, environmental, and operational barriers to the integration of lean manufacturing principles with Industry 4.0?

The remainder of the paper is structured as follows. In Section 2, the integration of Lean and Industry 4.0 will be explained in theory, followed by the research methodology in Section 3. Section 4 will focus on the results and the discussion where for each topic, the results will be presented and then discussed. Afterwards, Sections 5 and 6 will include the theoretical and managerial contributions, respectively. The paper will provide a conclusion in Section 7 and suggestions for future research in Section 8.

2 Integration of Lean and Industry 4.0

A detailed analysis has been carried out focusing on the integration of Lean and Industry 4.0. The foundations of Lean 4.0 go back to the invention of the Jidoka principle. In the late 1890s, the first mechanical automation concept in Toyota was invented by Sakichi Toyoda to relieve employees from the need to perform labour-intensive work (Liker, 2020). Utilising the newly emerged power of steam engines during the First Industrial Revolution, Jidoka originated as a principle that combined automation with the human touch where employees would stop the production if an abnormality such as a defect were detected. With electrification introduced by the Second Industrial Revolution, Jidoka evolved into an automatic process where machines would stop automatically and activate lights called Andon to notify employees. During the widespread digitisation era in the Third Industrial Revolution, Jidoka systems became equipped with sensors and hardware that helped people identify the causes of errors (Romero *et al.*, 2019). Currently, in the Fourth Industrial Revolution era, these systems are equipped with a wide range of sensors, actuators, and analytics tools that allow the early diagnosis of an error and perform self-correction before it can occur.

Jidoka is an example of how social aspects are an essential part of Lean 4.0 where concerns on employee welfare initiated the automation concept. Lean 4.0 continued to evolve in the social and environmental dimensions. The historical evolution of Lean and Industry 4.0 leading to their integration is displayed in Figure 1, where the social and environmental aspects are in green and yellow font. Notable events are also marked on the timeline, which shows the start of Lean 4.0 in 2011 with the introduction of Industry 4.0. In terms of social impact, one of the highlights occurred in 2016 through the introduction of the Work 4.0 vision by the German government (BMAS, 2015). Focusing on the reimagination of work through Industry 4.0, this vision highlighted the opportunities to develop the interaction between people and digital tools and offered insight into flexible work arrangements in terms of time and location. A further white paper on the subject mentions lean management's role in company performance and the importance of a skilled workforce to facilitate the new work vision (BMAS, 2017).

In terms of success factors of Lean, the theoretical research showed social aspects, such as leadership support, employee participation, teamwork, and a skilled workforce, play an essential part (Netland, 2016; de Sousa Jabbour *et al.*, 2018b; Moeuf *et al.*, 2020b). Similarly, some of the barriers inherent in Lean and Industry 4.0 have a social focus, such as employees' resistance to change, a lack of leadership, and ineffective management (Jadhav, Mantha and Rane, 2014; Raj *et al.*, 2020; Stentoft *et al.*, 2020). In addition, Lean is seen as a costly method with a high expectancy of failure and the loss of dedicated resources such as time (Atieh *et al.*, 2016). Industry 4.0 technologies also require a high initial investment, although the cost of the rest of the development is relatively lower (Tabanli and Ertay, 2013). Furthermore, some barriers to integration are inherited from individual paradigms, such as security concerns linked to implementation involving Industry 4.0 (Horváth and Szabó, 2019).

Nonetheless, regardless of risk and barriers, the implementation of Lean and Industry 4.0 presents considerable benefits. In terms of social benefits, Lean and Industry 4.0 allow better communication, employee empowerment, and flexible working, which are also highlighted in Work 4.0 (BMAS, 2017; Tortorella and Fettermann, 2018). Further, in recent years, there has been an increase in research linking Lean and Industry 4.0 to green and sustainable supply chains to understand possible environmental benefits (de Sousa Jabbour *et al.*, 2018b; Varela *et al.*, 2019; de Giovanni and Cariola, 2020; Kamble, Gunasekaran and Dhone, 2020). In practical cases, the integrated use of Lean and Industry 4.0 has helped monitor resource use, such as energy (Verma and Sharma, 2016). As displayed in Figure 1, recent developments in environmental dimensions included the World Economic Forum's white paper in 2018 to encourage Industry 4.0's role in driving sustainable manufacturing (Leurent and Abbosh, 2018).

Additionally, in recent years, one of the more popular topics of research about Lean and Industry 4.0's integration is determining the correct order of application. While the Jidoka example shows automation's introduction before the invention of Jidoka, there is significant interest in research focusing on Lean's application first followed by Industry 4.0. Furthermore, the framework 'Lean first then automate' was developed and used in various case studies

(Bortolotti and Romano, 2012), and some research highlighted Lean's role as an enabler for the adoption of Industry 4.0 (Prinz, Kreggenfeld and Kuhlenkötter, 2018; Bittencourt, Alves and Leão, 2019; Rossini, Costa, Staudacher, *et al.*, 2019; Chiarini and Kumar, 2020). Similarly, technology such as automation needs to support people and be tailored to specific processes, as incorporating technology in inefficient processes will only magnify the inefficiency (Liker, 2020). There is research on the application of Industry 4.0 first to serve as an enabler and reinforcer of Lean, but such studies have been limited (Lorenz *et al.*, 2019). As a result of these different views, there has not been agreement on the subject. Further, this topic was accompanied by research on whether Lean and Industry 4.0 contradict or complement each other. Overall, studies have shown a synergetic relationship between Lean and Industry 4.0, whereas some have identified minor contradictions (Lorenz *et al.*, 2019; Tortorella *et al.*, 2020).

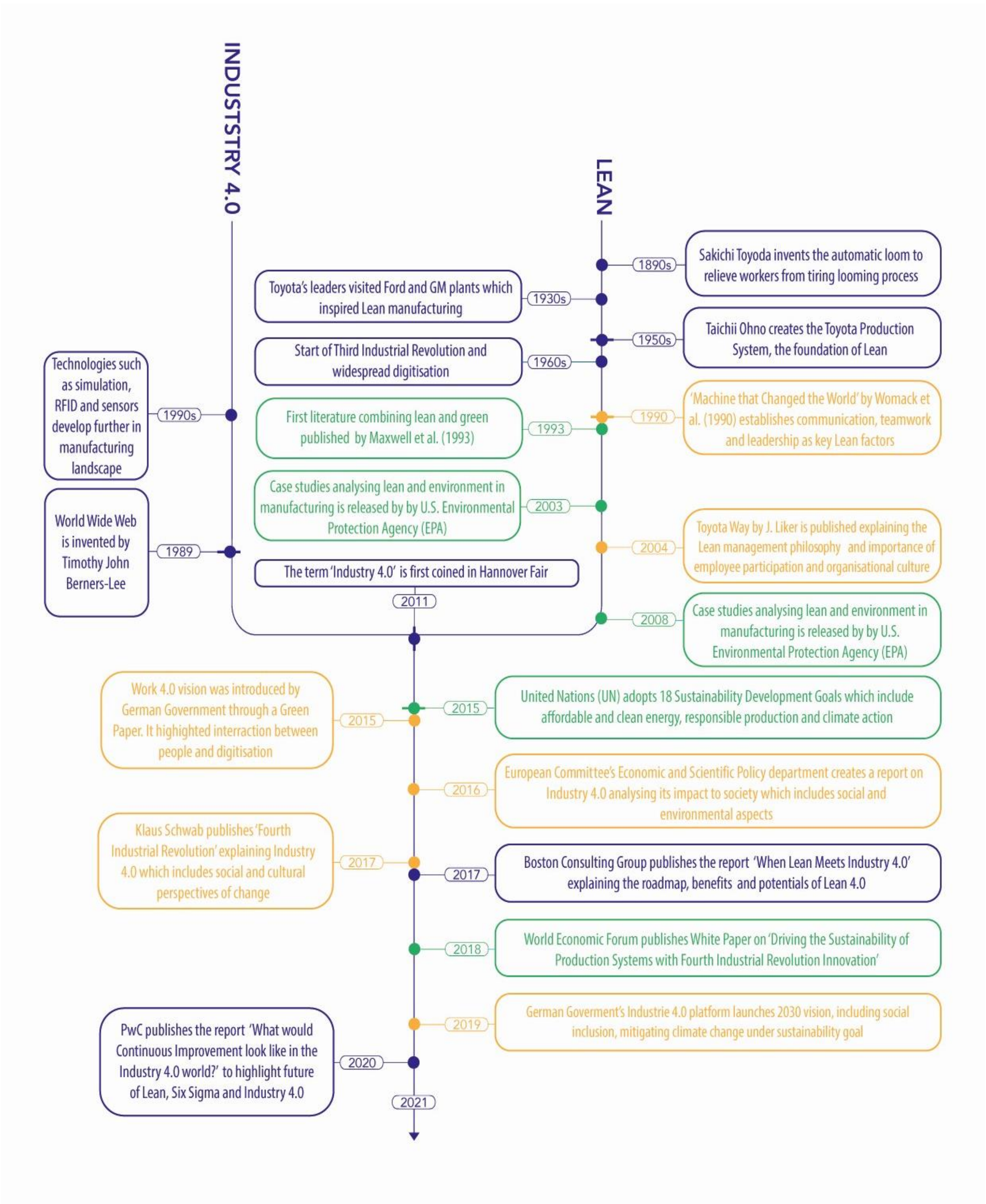


Figure 1. Timeline of Lean 4 and Industry 4.0 evolution with operational, social, and environmental focus

3 Methodology

The methodology used for this research was a systematic literature review, which was used to analyse the literature in a structured manner. The aim of the literature search strategy was to gather papers that included the application, implementation, and case studies of specific lean manufacturing principles together with Industry 4.0 tools in real-life production environments. After applying inclusion and exclusion criteria, the selected papers were analysed for benefits, barriers and critical success factors looking at social, environmental, and operational perspective.

The methodology consisted of four steps: identification, screening, eligibility, and inclusion, as shown in Figure 2, where the flowchart structure was adapted from the PRISMA flow chart (Moher *et al.*, 2009). A rigorous protocol of inclusion and exclusion criteria and limited keyword selection was applied to keep the research focused on displaying industrial case studies.

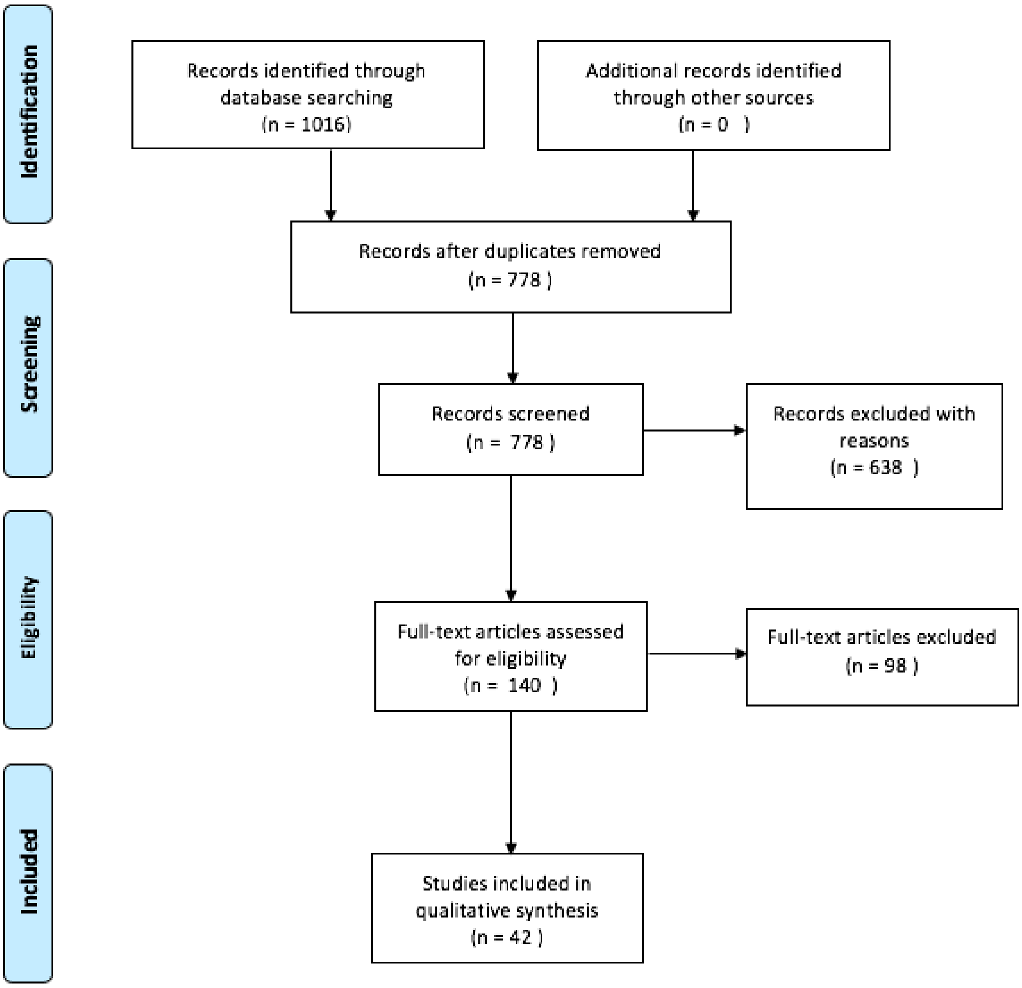


Figure 2. Flowchart for this literature review

The identification phase was initiated with determination of the database; Scopus and Web of Science were selected as the two key databases for the literature search. The search time frame started in 2011, which marked the introduction of Industry 4.0 at Hannover Fair (Núñez-Merino *et al.*, 2020). The end of the period is 5 December 2020, which is the date papers were downloaded from the databases.

As Lean and Industry 4.0 are both umbrella terms with an extensive keyword range, the selection was limited to 10-11 keywords for Lean and Industry 4.0 as shown in A and B, respectively in Table 1. The selected keywords specifically focus on principles and tools that relate inside the organisation and excluded any customer or other supply chain elements. The aim was to bring Lean principles to include more manufacturing operations context, which will be explained further in inclusion criteria. To incorporate research on a manufacturing context, column C was added. Further, the words ‘Lean’ and ‘Industry 4.0’ are excluded from keywords intentionally to target the right scope and align search criteria with the research aim. For example, if a company is ‘using Lean’ or ‘implementing Industry 4.0’, this can cause ambiguity and does not provide enough context for analysis. The aim of the literature search is to gather specific practical applications, which should include details of tools used, with terms such as ‘kanban’, ‘jidoka’ for Lean and ‘sensor’ or ‘RFID’ for Industry 4.0. To ensure this process does not miss any paper, the search was repeated by the first author only including Industry 4.0 and Lean to column A in Table 1. Randomly selected 200 papers were screened using of title and abstract, however no paper was identified. Also, the words ‘benefit’, ‘barrier’ and ‘success factor’ are not included because they are aimed to be deducted from the analysis and their inclusion would not result in case studies.

Table 1. List of keywords used for literature search

LEAN (A)	**INDUSTRY 4.0 (B)**	**CONTEXT (C)**
	B1	
value stream map*	RFID	manufacturing OR production
Kanban	Sensor	
Heijunka	Actuator	
Jidoka	auto*	
poka-yoke	robot*	
Andon	Reality	
5S	Cloud	
just-in-time production	Simulation	
SMED	**B2**	
Kaizen	Artificial Intelligence OR AI	
	Cyberphysical System OR CPS	
	Internet of Things OR IoT	
	Digital Twin	

The search was done in two iterations for both databases, making a total of four batches. The first iteration used Industry 4.0's technological tools with A, B1, and C, and the second iteration used systems as in A, B2, and C. An example of the search phrases for Scopus is displayed in Table 2.

Table 2. List of search phrases used for Scopus search

	Scopus
Iteration 1	(TITLE-ABS-KEY ("Value Stream Map*" OR kanban OR heijunka OR jidoka OR poka-yoke OR andon OR 5s OR "just-in-time production" OR smed OR Kaizen) AND TITLE-ABS-KEY ("RFID" OR sensor OR actuator OR auto* OR robot* OR reality OR cloud OR simulation) AND TITLE-ABS-KEY (manufacturing OR production)) AND DOCTYPE (ar) AND PUBYEAR > 2010
Iteration 2	(TITLE-ABS-KEY ("Value Stream Map*" OR kanban OR heijunka OR jidoka OR poka-yoke OR andon OR 5s OR "just-in-time production" OR smed OR Kaizen) AND TITLE-ABS-KEY ("Artificial Intelligence" OR ai OR "big data" OR "Internet-of-Things" OR "cyber-physical systems" OR iot OR cps OR "digital twin") AND TITLE-ABS-KEY (manufacturing OR production)) AND DOCTYPE (ar) AND PUBYEAR > 2010

In order to narrow the search to focus on peer-reviewed journal articles, the search was filtered to include only peer-reviewed articles. After the timeframe, keywords, and databases were determined and the filter was applied to include 1,016 papers, downloaded in 4 batches.

In the next step, duplicates were removed and the remaining 783 papers were screened through their abstract, keywords, and title. In this screening stage, inclusion and exclusion criteria were applied to categorise the papers, as displayed in Table 3, which shows the distribution in each category. At the start of the screening process, randomly selected 30 articles from 783 papers were coded by all three authors and any discrepancies identified in the coding process were resolved. This helped in improving the reliability of the coding process. Thereafter, the remaining papers were reviewed by the first author following the agreed coding standards. In addition, a random sample of papers at each stage was also reviewed by the two co-authors to ensure high reliability, accuracy and quality of the coding process.

At the screening stage, 638 papers were excluded as they were classified as not related (NR) and loosely related (LR). The inclusion criteriawas used to check if that case studies were applied in real-life manufacturing environments or used data from collected from there. Manufacturing plants are complex environments where scheduling, demand, and workforce can affect performance in a way that cannot be created in a theoretical set-up. Hence studies that used theoretical, experimental data, including floor set-ups, were not included and these cases were discarded as LR1 (see Table 3). Any implementation that used real manufacturing data in an experimental set-up was included e.g. using real cycle-time of a product to simulate the current situation of a production line.

For the eligibility stage, 140 papers, which were deemed to be partially and closely related in Table 3, were included for a full-text review. The inclusion criteria at this stage were that the case study to include a manufacturing operation where manufacturing is defined as ‘the processing of raw materials or parts into finished goods through the use of tools, human labor, machinery, and chemical processing’ (Kenton, 2021). For example, the case study in Chen et al. (2013) focused applying RFID and Value Stream Map explicitly on the warehouse and logistics and did not include any manufacturing processes. A total of 42 practical case studies were selected for the study, and the remaining 98 papers were excluded as being only partially related.

Table 3. Exclusion and Inclusion criteria with number of papers in each category

CRITERIA		EXPLANATION	NO OF PAPERS
Excluded	Duplicates (DUP)	Duplication of same paper	238
	Without Full Text (WF)	Full text not available to the author	47
	Not Related (NR)	NR 1 - A paper is not a peer-reviewed academic article, e.g., conference review, book chapter, editorial material etc.	16
		NR 2 - A paper is not related to Lean or Industry 4.0 in context, e.g., a medical paper.	141
	Loosely related (LR)	LR1 - A paper is not a case study and does not contain application or implementation using real-data. e.g., literature review, framework etc.	17
		LR2- The paper is not in the manufacturing context, e.g., services or healthcare industry	192
		LR3- Lean is used only as an exemplary fact, expression, or keyword.	41
		LR4 - Industry 4.0 term is only used as an exemplary fact, expression, or keyword.	184
	Partially Related (PR)	PR - A study includes lean and Industry 4.0 tools but focuses on a part of factory, not including the manufacturing process, e.g., a case study in a factory warehouse	98
Included	Closely Related (CR)	CR - Lean principle is explicitly integrated with Industry 4.0 technology	42

4 Results and Discussion

4.1 Overview of Case Studies

The literature was analysed in terms of year, sector, and how these lean and Industry 4.0 tools are integrated. The distribution of literature by year is conveyed in Figure 3. Between 2011 and 2018, the average number of case studies was three per year, which was followed by a considerable increase in 2019. The data shows that 45% of the selected papers were published after 2019, demonstrating that it is an emerging topic that has been accumulating increased interest in recent years.

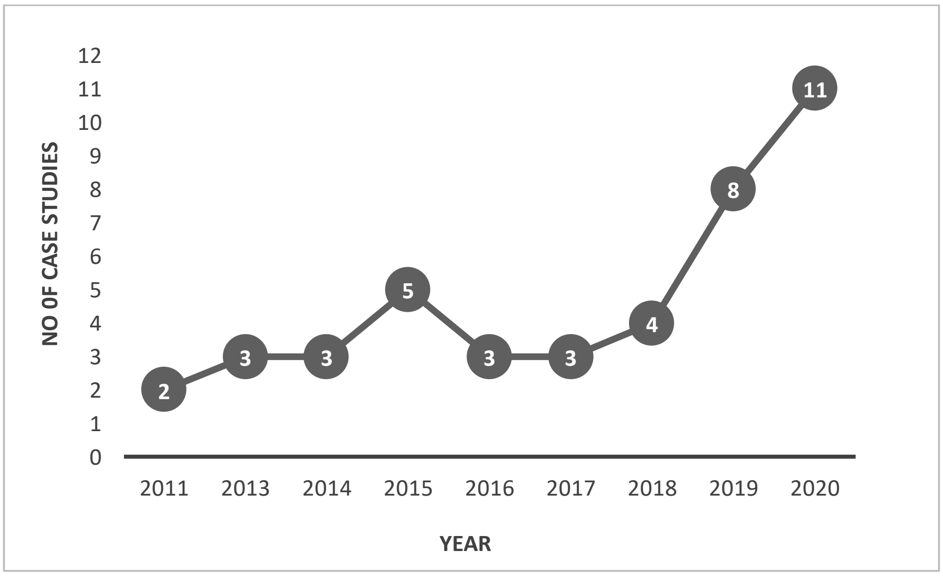


Figure 3. Number of papers included by year

The distribution of the literature according to different sectors is displayed in Figure 4, showing that a variety of sectors, from furniture to plastics, are in the study. In 14% of case studies, the sector has not been disclosed. The majority of the case studies (39%) took place in automotive plants. As the foundations of Lean were developed in Toyota's automotive plant (Holweg, 2007), the transferability of the practice has been easier through this sector. Furthermore, the automotive industry is one of the main economic pillars of developed countries like the UK, where the government's figures show that the automotive sector contributes £40bn to export revenue and 390,000 highly paid jobs (Clark and Stein, 2018). Hence, beneficial continuous improvement or digitisation initiatives in the automotive sector would significantly benefit a country's economy. With this aim, governments of countries such as the UK and Germany encourage and invest in research on digitisation and continuous improvements in the automotive sector. For example, the benefits gained through digitisation of the UK automotive sector are estimated to reach £74bn by 2035 (SMMT, 2017), thus explaining the increased application in this sector.

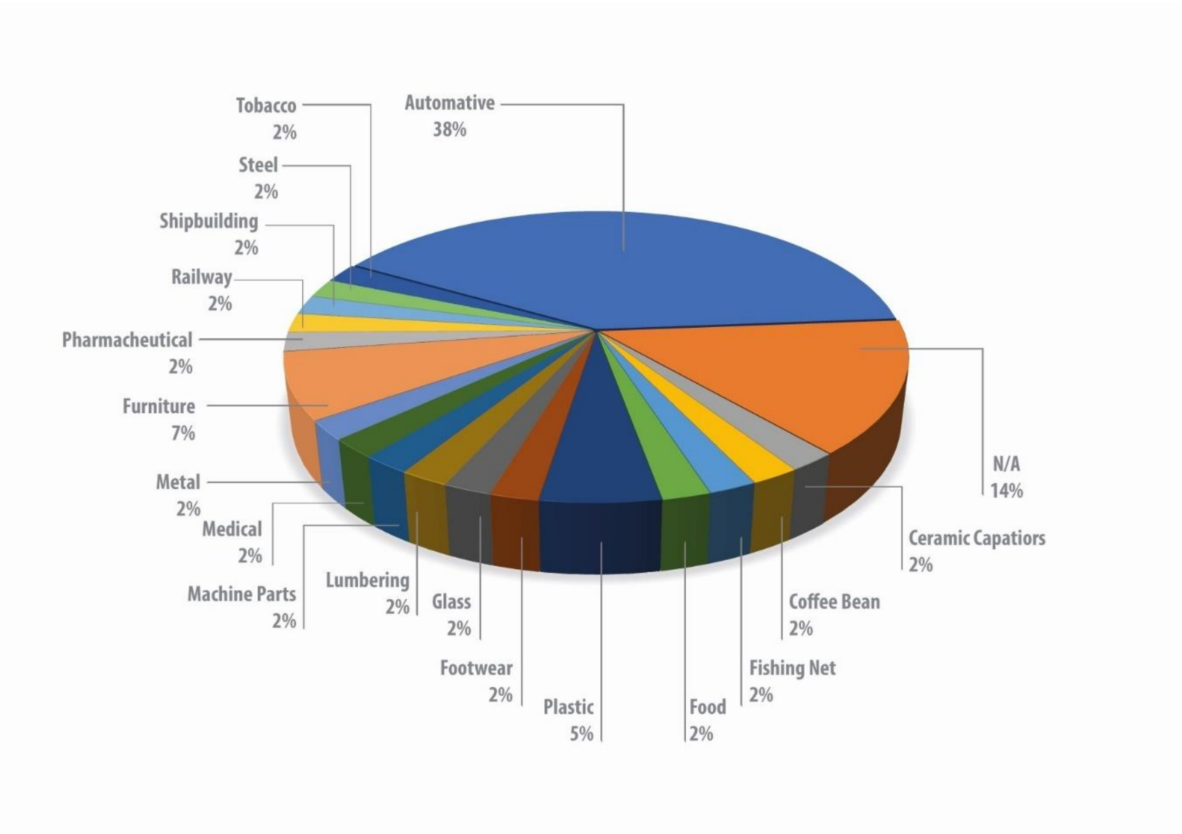


Figure 4. Number of papers included by sector

4.2 Order of Application of Lean and Industry 4.0

In case studies, Lean and Industry 4.0 have been applied in different orders, as displayed in Figure 5. In 40% of the case studies, both were applied simultaneously as a set plan to address a manufacturing plant's problem. Regardless of company size and industry, the majority of simultaneous Lean and Industry 4.0 applications involved using a combination of value stream mapping (VSM) and simulation tools explained in the next section.

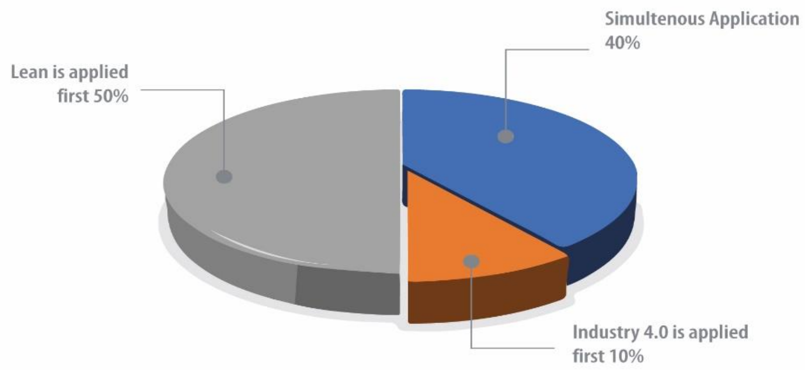


Figure 5. Distribution of papers according to application order of Lean and Industry 4.0

Lean principles were applied before Industry 4.0 in 50% of the case studies. In these implementations, Industry 4.0 mostly acted as a reinforcer or enabler for the benefits of lean principles. It is important to note that Lean is a very popular method among manufacturing, and existing lean practices are expected in manufacturing plants, which can possibly account for the popularity of Lean first implementation. This was the case especially in automotive plants, where the majority of the Lean first applications took place. As Lean was first discovered and applied in an automotive plant of Toyota, its practices transferred easily and spread through the same industry. For example, an automotive parts manufacturer in the study by Phumchusri and Panyavai (2015) already had a Kanban system before Industry 4.0 introduction. As the manual Kanban system had some errors and difficulties such as lost Kanban cards, electronic Kanban (E-Kanban) was introduced as a solution where cards are maintained and signalled electronically. Using electronic signals, E-Kanban systems create a virtual system to collect data and notify the downstream process that products are required (Pekarcikova *et al.*, 2020). Human errors can be eliminated by switching from a manual system to a dynamic e-Kanban system, and the process flow can be automatically regulated. As a result of this switch, a rubber seal producer reduced delays from 75.11% to 11.79% (Phumchusri and Panyavai, 2015).

In only 10% of the literature, lean principles were applied later, whereas Industry 4.0 technology was frequently used as an enabler for Lean. As an example, enterprise resource planning (ERP) software was used to enable just-in-time (JIT) production in a manufacturing plant in Turkey (Erkayman, 2019). ERP integrated the business processes both vertically and horizontally to illustrate a holistic picture of the whole business. A high inventory problem was addressed through this application, and the later inventory was eliminated with the introduction of JIT production. In terms of the order of implementation, this study shows that a successful through applying Lean first, last, or simultaneously with Industry 4.0. It has been observed that one of the main decision points of the application order is a company's aim and existing resources. As in the previous example, in a company with an existing ERP infrastructure, applying JIT proved beneficial (Erkayman, 2019).

However, this does not prove that applying Industry 4.0 tools first or simultaneously would be equally beneficial in certain situations. While previous studies support the view that the first application of Lean would improve the benefits of Industry 4.0 (Prinz, Kreggenfeld and

Kuhlenkötter, 2018; Bittencourt, Alves and Leão, 2020), this study proves the possibility of both simultaneous and Industry 4.0 application first is also beneficial. To reach a conclusion on the correct order of application, there needs to be future research on the role of a company's improvement aim, industry and the existing resources.

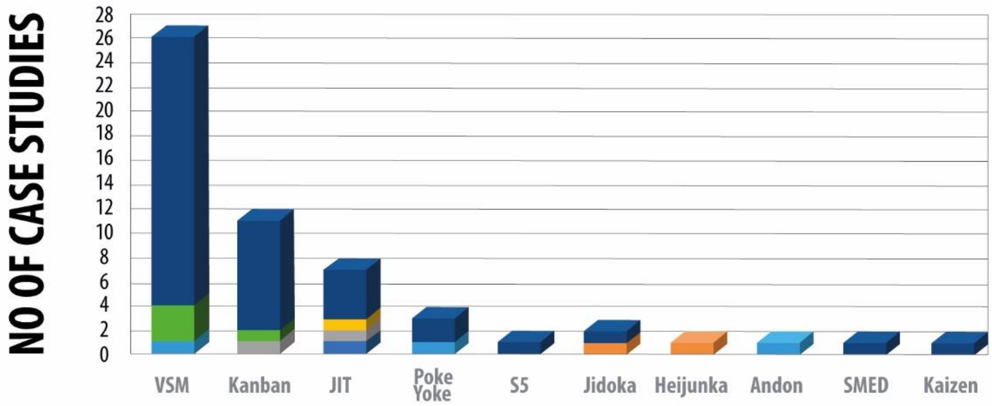
4.3 Integration of Lean Principles and Industry 4.0 Tools

Through the application of Lean and Industry 4.0, companies aimed to address certain problems. These are displayed in Table 4 along with the key performance indicators (KPIs) used in studies to measure the related variables. The table did not include the case studies that did not explicitly address companies' aim for the initiative or KPIs. Table 4 shows a variety of different aims for Lean and Industry 4.0 applications; the majority are concerned about the economic application, such as reduced lead-time and cost. Taking account of social and environmental aspects, only two of the case studies included environmental concerns and social welfare as the aim for improvement (Boudella, Sahin and Dallery, 2018; Baumer-Cardoso et al., 2020). The case studies showed that the driving force of Lean and Industry 4.0 integration focused on gaining economic benefits similar to previous theoretical research. Table 4 describes the main problem addressed in the case studies.

Table 4. Integration of Lean and Industry 4.0 by literature

Problem	Solution / Aim of Application	Combination		KPI	Authors
		Lean	Industry 4.0		
Machine Failures	Create a preventative maintenance plan	JIT	Simulation	Failure rates (%) Times to failure/repair Availability	(Mendes and Ribeiro, 2014)
Machine Reliability	Increase reliability Decrease machine downtime	Poka-Yoke	Simulation	Downtime (%)	(Ahmed Abed et al., 2020)
Quality Issues	Introduce Zero Defects	Poka-Yoke	IoT	Customer Claims (%)	(Wijaya *et al.*, 2020).
	Identify and eliminate waste	VSM	Simulation	Throughput (units) Lead-Time (min)	(Lyu, Chen and Huang, 2020)
Low Productivity	Increase production capacity to manage fluctuating demand	VSM	Simulation	Throughput (units per day) Cost ($)	(Helleno *et al.*, 2014)
	Increase production capacity to improve bottleneck utilisation	VSM	Simulation	Lead-Time (min) Efficiency (%)	(Parthanadee and Buddhakulsomsiri, 2014)
	Increase production capacity to meet customer demand	VSM	Simulation	People Productivity (%) Value Added Per Person (%) Floor Space Utilisation (E/m2)	(Parv *et al.*, 2019)
	Identify and eliminate waste and bottlenecks	VSM, Kaizen, Kanban, JIT	Simulation	WIP (units) Lead-time (s) Throughput (s)	(Munyai *et al.*, 2019)
	Increase throughput	Poka-Yoke	Simulation	Throughput (unit) Cost (RM)	(Ab Rashid *et al.*, 2015)
Long Lead-time	Identify and eliminate waste	VSM	Simulation	Lead-time (days)	(Guner Goren, 2017)
	Identify bottlenecks and increase utilisation of resources	VSM	Simulation	Lead-time (hours) Overall Equipment Effectiveness (OEE (%)	(Alzubi *et al.*, 2019)
	Increase service level	VSM Kanban	Simulation	Service Level (% of orders completed)	(Yang *et al.*, 2015)
	Identify and eliminate waste Identify bottlenecks and increase utilisation of resources	VSM	Simulation	Lead-time (days)	(Atieh *et al.*, 2016)
Long Delays / Waiting	Identify and eliminate waste	VSM	Simulation	Lead-time (days)	(Andrade, Pereira and Del Conte, 2016)
	Identify and eliminate waste	Jidoka 5S Kanban	Simulation	Delay Rate (%) Material Replenishment Rate (%) Defect & Rework Rate (%)	(Guillen *et al.*, 2018)
	Decrease the number of delays	Kanban JIT	E-Kanban Big Data	Delays (no)	(Phumchusri and Panyavai, 2015)
High Inventory	Implement real-time monitoring for production	JIT	ERP	Inventory ($)	(Erkayman, 2019)
	Decrease Inventory	VSM	Simulation	Inventory (units)	(Midilli and Elevli, 2020)
High Costs	Cut Costs	VSM Kanban	RFID	Cost Saving (€) Return on benefit (€)	(Tabanli and Ertay, 2013)
Environment and Sustainability Concerns	Identify and monitor resource consumption	Kanban VSM	Simulation	Material Consumption (kg) Water Consumption (l) Energy Consumption (kWh)	(Baumer-Cardoso *et al.*, 2020)
Lack of visibility of production status	Track the manufacturing process and performance	VSM	RFID	Lead-time (min)	(Chen, Chen and Cox, 2012)
Labour-Intensive, time consuming processes	Increase efficiency of kitting process	JIT	Robots Automation	Lead-Time (s)	(Boudella, Sahin and Dallery, 2018)

The combination of Lean and Industry 4.0 used in all the case studies to address the problems present in manufacturing companies is presented in Figure 6. The results are distributed focusing on lean principles on the x-axis and the accompanying Industry 4.0 tools underneath the graph in a table format.



	VSM	Kanban	JIT	Poke Yoke	5S	Jidoka	Heijunka	Andon	SMED	Kaizen
Simulation	22	9	4	2	1	1			1	1
RFID	3	1								
IoT	1			1				1		
Robots			1							
Big Data		1	1							
CPS						1	1			
ERP			1							

Figure 6. Integration of lean principles with Industry 4.0 in case studies

VSM and simulation were the most frequently applied tools in case studies., VSM and simulation were used individually in 62% and 81% of the total case studies, respectively. Their integration was present in 52% of the total number of studies.

The high number of cases using VSM can be explained through its function in lean management. VSM is needed to apply the first two principles of Lean; it displays the current and desired future state (Tyagi and Vadrevu, 2015). It enables the application of other lean principles, such as Kanban and JIT, to establish process flow and pull production. As it is an initial step and an enabler for other lean principles, it is frequently used in Lean implementation. In most case studies, VSM was applied either before the Industry 4.0 tool or simultaneously. One of the reasons for its popularity is its simplicity and costless application, requiring only a pen and some paper (Martin and Osterling, 2013). Similarly, simulation is one of the more cost-effective tools of Industry 4.0, allowing the virtual representation of a physical system or a process that makes it possible to compare changes in a system (Stump and Badurdeen, 2012). Due to its versatility to adapt to systems and evaluate changes, it is one of the most popular methods, and in the context of Industry 4.0, simulation is considered one of the nine main pillars (Rüßmann, 2015).

Through the integration of VSM and simulation, many of the case studies created digital copies of the production system. Some of the digital copies were created for the current state of the production line to identify bottlenecks and problems (Alzubi *et al.*, 2019; Munyai *et al.*, 2019). The remainder was used for future or current states to convey the impact of different improvement scenarios to aid decision making (Parthanadee and Buddhakulsomsiri, 2014; Trebuna, Pekarcikova and Edl, 2019; Liu and Yang, 2020). Further, these simulations have shown compatibility with real systems. In the case study by Ito *et al.* (2020), the real manufacturing output was compared with the simulation, which showed 96.77% compatibility. Additionally, the hypothesis tested by Parthanadee and Buddhakulsomsiri (2014) used simulation data that was run over a year to compare the actual operational data and concluded that there is no significant statistical difference between them.

By introducing simulation, VSM was fed with real-time data which added dynamism to the system and allowed more than product families to be conveyed (Chen *et al.*, 2013; Alvandi *et al.*, 2016). VSM is an essential lean tool; however, it has certain limitations, which are frequently mentioned in the literature (Stadnicka and Litwin, 2019; Liu and Yang, 2020), and it was complemented by simulation in many studies. One of the drawbacks is that traditional VSM presented a static view conveying a particular moment in time for a single product. Hence, it had a limited ability to represent a complex manufacturing system realistically. Real-time data was also supplied by other technologies, such as RFID and IoT, which enabled VSM to monitor operational variations in real time (Antosz and Pacana, 2018). Live operational data can be collected and identified using sensors and RFID, which stands for Radio-frequency identification. Further, IoT allows this live data to be connected, distributed and displayed through the use of internet. In this context, the data collected is distributed and processed in to the process framework created by VSM.With a similar aim of monitoring the production, Chen and Chen, 2014) introduced a system called ORFPM, which stands for online radio frequency identification (RFID)-based facility performance monitoring.

Simulation is also frequently used with JIT and Kanban (Mendes and Ribeiro, 2014; Azouz and Pierreval, 2019; Munyai *et al.*, 2019). For example, a drug process plant utilised simulation to design and optimise a JIT material handling system for production (Ezema, Okafor and Okezie, 2017). The optimisation is essential for Kanban systems where the variables, such as the number of feeders and lot sizes, can be optimised through the simulation of possible scenarios (Che Ani, Kamaruddin and Azid, 2018). Further, the research by Ma, Wang and Zhao (2017) used automation and robots to feed parts to a JIT assembly line. Following on the automation context, Li (2018) proposed a smart automation system combining IoT, RFID, and sensors.

In terms of Industry 4.0 tools, the application complexity has been limited compared to the potential presented by advanced digitisation and smart factory concepts. Only a limited number of case studies included advanced Industry 4.0 systems, such as cyber-physical systems (CPS), Internet of Things (IoT), and artificial intelligence (AI). Similarly, there has been extensive use of simulation, but none of the case studies extended its application to a more advanced setting, such as Digital Twins. More specifically, the Digital Twin system creates a virtual representation of physical objects in a factory harmonising physical and virtual data for optimisation (Ding *et al.*, 2019; Tao *et al*., 2019). This proves that the practical implementation of Industry 4.0 in real life is in its infancy compared to the opportunities presented by theoretical work. Hence, Industry 4.0 needs further development and perhaps additional resources to adapt to practical cases and lean principles.

Some lean manufacturing tools, such as Heijunka, Jidoka, SMED, and Kaizen, are not mentioned as frequently as other lean principles, such as Kanban and JIT. One of the reasons could be the need for improvement of these principles. In most case studies involving VSM and Kanban, Industry 4.0 tools are used to address a problem in these lean principles and increase the efficiency of the application. Principles like 5S and Poke-yoke are comparably simple to apply and have limited room for improvement; hence, their integration with Industry 4.0 is limited. Additionally, research into and interest in VSM and Kanban implementation has been more advanced in comparison to Jidoka, Heijunka, and SMED due to their potential use outside manufacturing. Further development of these principles has allowed improvements in workflow management where Kanban-inspired software is created for project management (Gould, 2018; Kanbanize, 2021). VSM has become a versatile principle which can be applied to broader administrative processes for improvement (Keyte and Locher, 2004). In the meantime, SMED and Jidoka principles are more specific to a manufacturing process concerning automation and machine tool change and so have limited broader implementation (Faccio, 2013; da Silva, 2016; Liker, 2020). Due to the limited use in a broader aspect, there is less interest in SMED and Heijunka implementation, causing the implementation to be lower in comparison.

4.4 *Benefits* – What are the benefits of integrating lean manufacturing principles and Industry 4.0 from an operational, social, and environmental perspective?

The benefits of these implementations are investigated from operational, social, and environmental perspectives according to a TBL approach, where harmonisation of the three aspects results in a range of benefits (Carter and Rogers, 2008). To adapt this categorisation to a manufacturing context, the economic aspects are represented as operational performance, and social aspects are aligned with employees and organisational culture limiting the scope to within the organisation. The TBL approach was used throughout the study to outline the possible intersection between these three aspects. Not all case studies mentioned operational, environmental, and social perspectives. In each section, only the case studies that included the named benefit are displayed in the given tables.

4.4.1 Operational Benefits

Operational benefits are described in terms of improvement in operational performance, which can be measured using KPIs. A summary of the operational benefits observed in the literature is displayed in Table 5. The case studies that reported improvement without supporting quantitative data are not included. These benefits are both resultant or predictive benefits through the analysis of future or suggested cases.

Table 5. Operational benefits by literature

KPI	Improvement	Authors
Throughput	Increase in throughput by 14.7% and 16.3% through Poke-Yoke and Standard Operating Procedures respectively.	(M. F.F. Ab Rashid *et al.*, 2015)
	Production output increased from 2 units to 5 units a day.	(Che Ani, Kamaruddin and Azid, 2018)
	Increase of production by 40%.	(Pekarcikova *et al.*, 2020)
	Increase of throughput by 25%.	(Xia and Sun, 2013)
	Increase of throughput by 63.30%.	(Munyai *et al.*, 2019)
Productivity	Productivity improvement by 173%.	(Ito *et al.*, 2020)
	People productivity increased by 30%. Floor space utilisation increased 15 Euro/m^2	(Parv *et al.*, 2019)
	Plant efficiency increased from 90% to 96%	(Balaji *et al.*, 2020)
Efficiency	Efficiency of system improved 2.8 times.	(Midilli and Elevli, 2020)

Lead-time	Cycle time for three different customers dropped by 43.67%, 57.91%, and 58.39%	(Lyu, Chen and Huang, 2020)
	Lead-time decreased from 72.409 days to 31.124 days	(Trebuna, Pekarcikova and Edl, 2019)
	Lead-time decreased from 4.5 to 2 days.	(Liu and Yang, 2020)
	Lead-time decreased from 73.85 days to 7.3-9.1 days.	(Jordan *et al.*, 2020)
	Improvement in lead-time by. 41%	(Guner Goren, 2017)
	Reduced lead-time by 6%.	(Atieh *et al.*, 2016)
	Reduced lead-time by 7%.	(Andrade, Pereira and Del Conte, 2016)
	Reduced lead-time by 6%.	(Alzubi *et al.*, 2019)
Down-time	Reduction in downtime and waste by 0.71%	(Abed *et al.*, 2020)
Changeover time	Changeover time decreased by 64%	(Antosz and Pacana, 2018)
Delays	Delays reduced from 75.11% to 11.79% events	(Phumchusri and Panyavai, 2015)
Inventory	Reduction of WIP by 33.92%	(Yang *et al.*, 2015)
	Inventory worth 80,000$ - 1,00,000$ was eliminated completely	(Erkayman, 2019)
Cost	50% reduction in cost	(J Ma, Wang and Zhao, 2017)
	Reduced cost by 1,039.8 € a month	(Tabanli and Ertay, 2013)
Quality	Defective products were reduced from 18% to 10%, rework products were reduced from 7% to 3%.	(Guillen *et al.*, 2018)
	Customer claims went from 34.7% to 5.3%	(Wijaya et al., 2020)
Reliability	80% reliability for preventative maintenance have been established	(Alebrant Mendes and Duarte Ribeiro, 2014)

A wide range of benefits is presented in case studies, from lead-time, inventory, to reliability. In terms of throughput and productivity, substantial improvements were achieved. In the case study by Che Ani, Kamaruddin and Azid (2018), production throughput increased from 2 to 5 a day. In terms of productivity, floor space utilisation was used as a KPI in the case study by Parv *et al.* (2019), which increased by 15€ per m^2 from 30.6€ to 45.8€ per m^2. For reliability, this integration was used to construct a preventative maintenance plan that aimed to reduce the risk of a possible machine breakdown to 80%

Time was the most common measure used in the studies, where around 33% of operational benefits were reported in terms of lead-time. As one of the highlights, the case study by Schmidtke, Heiser and Hinrichsen (2014) used VSM with simulation to improve the lead-time from 11.4 to 1.4 days. Other time-related KPIs are changeover time and down time (Antosz and Pacana, 2018; Ahmed Abed *et al.*, 2020). Two inventory-related case studies were presented, where in Erkayman (2019), the inventory was eliminated completely, showing a cost-benefit of up to $1M. Further, in a case study by Tabanli and Ertay (2013), the main aim of applying Kanban and RFID was to reduce costs, which was accomplished with the reduction of around 1,000€ a month. Majority of the case studies that used time based KPI such as turnaround and delay time have used VSM as one of the Lean tools. The frequent use of VSM can be explained through the ability to break down the processes and calculate takt time for each.

Analysis of these case studies shows a wide range of operational benefits can be gained through the application of Lean together with Industry 4.0, as expected from the previous literature. The benefits of application are not limited to time, quality, cost, reliability, and inventory, as it is important to consider that these benefits are interconnected. For example, decreasing lead time would allow more products to be delivered in a selected time, which means an increase in throughput. Similarly, some benefits are hard to quantify, such as reliability, as machine breakdown can cause unexpected problems. In the case study by Mendes and Ribeiro (2014), a JIT flow was simulated with the failure, repair, and availability data to assess whether the system's reliability meets the daily demand. The simulation allowed the identification of critical parts and aided managers' decision making as required for investment in any maintenance strategy. A decreased defect rate has an environmental benefit as fewer resources are used.

4.4.2 Environmental Benefits

Table 6. Environmental benefits by literature

Environmental Benefit	**Lean**	**Industry 4.0**	**Case Studies**
Monitoring resource consumption to create environmental awareness.	VSM	Simulation	(Alvandi *et al.*, 2016)
	Kanban VSM	Simulation	(Baumer-Cardoso *et al.*, 2020)
Prevents excess fuel consumption.	Poka-Yoke	Simulation	(Ahmed Abed *et al.*, 2020)
Decrease in defect and rework rate.	Jidoka 5S Kanban	Simulation	(Guillen *et al.*, 2018)
	VSM	Simulation	(Midilli and Elevli, 2020)
	Poke-Yoke	IoT	(Wijaya *et al.*, 2020)

In recent years, manufacturing companies have been facing intense pressure to be aware of their environmental impact and take responsibility for the energy and material they are consuming (Kleindorfer, Singhal and Van Wassenhove, 2005).

The implementation involved in this literature review has created awareness of the environmental effects of manufacturing through the visualisation of resource use. An overview of the benefits is displayed in Table 6. In the case study by Baumer-Cardoso *et al.* (2020), VSM was integrated with simulation to measure the energy, material, and water consumption in a multi-product manufacturing environment. One of the aims was to analyse the effects of lean implementation on the environment. The study concluded that Lean is mostly beneficial to the environment, as the consumption of energy and materials decreased with the application. However, water consumption rose due to the injection moulding process, which requires water. Hence, this resulted in the opinion that Lean is not fully synergistic with the environment. A similar application was observed in a case study by Alvandi *et al.* (2016), where VSM was combined with simulation to determine the environmental effects of changing from gas ovens to electric. Switching to electric ovens caused a reduction in energy consumption; however, it caused higher CO_2 emissions, as gas is a comparably cleaner source of energy. In both case studies, there were trade-offs between different resources. Overall, the main benefit was that companies gained the ability to monitor resource consumption on VSM through simulation. Further, this helps visualise the environmental effects of their decision making.

Other environmental benefits have been observed in terms of decreased CO_2 emissions. In a theoretical study based in the automotive industry, material flow was modelled to integrate Kanban and Milk-Run routines (Simić *et al.*, 2020). A Milk-Run routine is a logistic methodology that aims to reduce the transportation and inventory cost through optimising time, route, schedule, and parts that need to be delivered from multiple suppliers (Sadjadi, Jafari and Amini, 2009). In a case study, Artificial Poka-yoke (APY) was proposed by Ahmed Abed *et al.* (2020) where simulations and modelling techniques were combined to enhance an electrical combustion engine's reliability. Similar to the Jidoka principle, APY stops an engine when a deviation is predicted. With a focus on increased reliability, this approach aims to prevent deviations resulting in the overconsumption of fuel. This application shows a potential benefit to a broader manufacturing context, as similar approaches could lead to more stable and reliable processes.

The integration of Lean and Industry 4.0 has clear benefits for the environment in terms of monitoring and decreasing resource consumption and reducing defects. As operational and environmental aspects intersect in a TBL approach, reducing defects has not only economic benefits but also means less material waste and avoids energy consumption through reworking. In case studies by Guillen *et al.* (2018), Midilli and Elevli (2020), and Wijaya *et al.* (2020), the application of Lean and Industry 4.0 led to a reduced defect and reworking rate. However, only two of the companies, Baumer-Cardoso et al. (2020) and Alvandi et al. (2016), had environmental awareness and benefit as the main aim for the application. Although not mentioned specifically, both companies can be classified as large enterprises, with one offering more than 100 products and the other had more than 3000 employees. Hence, only the large enterprises with assumingly larger resources have targeted environmental benefits using Lean and Industry 4.0. The rest of the case studies were more concerned with economic benefit through reduced resource use. Both of the environment focused applications have occurred in recent years, that is 2016 and 2020.

Overall, the restricted number of case study articles on integrated Lean and Industry 4.0 implementation have shown limited environmental benefits. The case studies focusing on the environment were scarce in comparison to operational case studies, as only two recent studies aimed to demonstrate any environmental benefit (Alvandi *et al.*, 2016; Baumer-Cardoso *et al.*, 2020). The variety of benefits was limited to reduction in CO_2 emissions and in resource use including reduced defect and less reworking. However, there are many other environmental benefits that can be gained from this integration. The aspects such as facilitating the use of renewable and sustainable energy and increasing recycling were not mentioned in any of the case studies or in the theoretical research. As this link between Lean, Industry 4.0, and the environment is an emerging topic as seen from Figure 1, there is a possibility that in the future, there will be more case studies involving the environment. This can be supported by the fact that two case studies were published in 2016 and 2020. To allow for wider environmental benefits of Lean and Industry 4.0, there needs to be more research on applying, testing, and further developing theoretical models involving renewable energy and recycling in a practical setting.

4.4.3 Social Benefits

In the context of this research, social benefits are defined in terms of employee welfare relating to their health, their work quality, and their capacity to communicate and collaborate with each other to solve problems, negotiate, and lead (Srinivasan *et al.*, 2020). The social benefits in this study specifically focus on employees and do not go outside the organisation. An overview is given in Table 7. One of the key benefits related to improving employee welfare is fewer accidents. Moreover, preventing machine failures can help to minimise the risk of accidents. In the case study by Mendes and Ribeiro (2014), simulation is combined with JIT production to create a maintenance plan to improve reliability and prevent any possible accidents that could arise from machine failure. In a separate study, the use of VSM with simulation has helped increase work quality and reduce accidents by identifying a suitable supply policy between workstations (Dotoli *et al.,* 2014).

Table 7. Social benefits by literature

Social Benefits	**Lean**	**Industry 4.0**	**Case Studies**
Reduced risk of accidents	JIT	Simulation	(Mendes and Ribeiro, 2014)
Relief of tiring labour-intensive work	JIT	Robots Automation	(Boudella, Sahin and Dallery, 2018)
Better communication Employee empowerment	Kanban JIT	Simulation	(Che Ani, Kamaruddin and Azid, 2018)
Help/improve decision making	Andon	Simulation, IoT	(Ito *et al.*, 2020)
	VSM	Simulation	(Jordan *et al.*, 2020)
	VSM	Simulation	(Helleno *et al.*, 2015)
	VSM, Heijunka,, Kanban	RFID, simulation, CPS	(Huang *et al.*, 2020).

Industry 4.0 tools release employees from tiring physical work, as automation and robotics are added to the systems to help employees perform repetitive and labour-intensive processes (Jing *et al.*, 2013). Further, hybrid operations that combine both people and robots are designed for systems where technology has not advanced sufficiently to allow robots to perform the whole process (Wrigley, 2015; Boudella, Sahin and Dallery, 2018). Through hybrid systems, employees still participate in the process. Further, they can use their expertise and extra capacity to engage in other improvement activities (Chui, Manyika and Miremadi, 2016).

Another social benefit is better and clearer communication between people and departments. As a lean tool, VSM can identify the flow of communication and information and materials (Ishak, Johari and Dolah, 2018), but Industry 4.0 also establishes the communication channels for both horizontal and vertical value streams. In a case study by Che Ani, Kamaruddin and Azid (2018), Kanban was combined with simulation to establish better communication between the materials warehouse and the production floor. While this application resulted in several benefits, such as reducing waiting time by 36.64%, most importantly, it encouraged employees to seek other further improvement activities, such as Kaizen. Moreover, an additional benefit is that Lean and Industry 4.0 implementation instils a sense of accomplishment and empowerment in employees, encouraging them to continue with process improvement in further activities.

Industry 4.0 technology can aid managers' decision making when combined with lean principles. Moreover, simulations can create different scenarios and visualise the outcomes of certain decisions. These outcomes accompanied by data, such as costs, can help decision makers to decide on the implementation of possible improvement scenarios (Jordan *et al.*, 2020). For example, when faced with a fluctuating demand problem, Helleno *et al.* (2015) used simulation with VSM to display the effects of possible solutions which were doubling the production line or acquiring new technology. Moreover, combined with Kanban simulations, decision makers can select the necessary parameters to optimise the solutions (Azouz and Pierreval, 2019). Along with effects, trade-offs can also be identified (Alvandi *et al.*, 2016).

Overall, the main social benefits were better communication, improved decision making, and improved welfare. In none of the case studies, the company's main aim was to improve social aspects; any such benefits gained through application were viewed as a bonus. However, when compared to environmental benefits, which were limited to resource use, social aspects had a more concrete impact, such as relief from tiring work and reduced accidents. In addition, there may be more benefits of Lean and Industry 4.0 implementation that was not mentioned. As most of the case studies focused on operational benefits, they did not recognise or measure social benefits during the application. For example, an analysis of case studies integrating VSM and simulation shows that some reported improved decision making, while others did not mention the implications of the practice to the employees. In an example beyond case studies, COVID-19 has brought a concept of social distancing and a requirement to work from home where possible. Using integrated Lean and Industry 4.0 features, such as real-time monitoring, interconnected networks, and workflow-management software inspired by Lean, employees at plants can work from home or in a more flexible manner, which would not have been possible otherwise (BMAS, 2015). However, recognition of this as a benefit has been limited in academia and industry. Therefore, there needs to be more research focusing on social dimensions. In summary, Lean and Industry 4.0 have contributed to social benefits through case studies, but more research is needed to discover the full extent and scope of the social impact.

4.5 *Success Factors* –What social, environmental, and operational factors have contributed to the success of the case studies?

The majority of the success factors identified in case studies were associated with social perspectives relating to organisational culture and employees. Moreover, the case study by Xia and Sun (2013) pointed out that Lean is a people-focused paradigm. As a result, certain social principles need to be preserved for Lean's combined implementation with Industry 4.0 to succeed. As a requirement for success, the study has emphasised that technology integration should not shift the focus from employee interaction. Lean principles based on social aspects related to employee empowerment and organisational learning are essential to a successful journey (Liker, 2020). In the context of organisational culture, successful implementation is also dependent on the ability and motivation to tackle problems creatively (Ezema, Okafor and Okezie, 2017).

Top management support and leadership have been identified as important in papers where lack of support could unintentionally sabotage transformation efforts (Worley and Doolen, 2006). Management support can alleviate the risk of employees ignoring the change and so minimise resistance (Erkayman, 2019). Simulation is frequently used to show the benefits of projects to gain management approval (Alzubi *et al.*, 2019). By visualising operational benefits, management can understand the necessity and thus, be encouraged to support the implementation (Jarkko *et al.*, 2013). This relationship between operational benefits and management support conveys another intersection of the social and economic perspectives.

Furthermore, employee participation has been a critical success factor for both Lean (Knol *et al.*, 2018) and Industry 4.0 (de Sousa Jabbour *et al.*, 2018c) in the literature beyond case studies. The expertise and knowledge of employees have been extensively used in VSM activities to identify and implement improvement activities (Balaji *et al.*, 2020). In a case study in Turkey, the involvement of process experts was identified as a significant success factor (Erkayman, 2019). Further, the paper identified an extensive list of success factors where the transparency of team leaders in explaining the process to employees, the preparation of managers, and the systematic implementation of the project have been highlighted as making an essential contribution.

As a key benefit, the combination of Industry 4.0 and Lean enhances communication through both vertical and horizontal integration. Better communication also facilitates the success of implementation. In case studies, ERP and RFID were used to create a platform for top management to communicate with the factory floor through monitoring measurements and tracking assets, which was one of the causes of success (Chen, Chen and Cox, 2012; Erkayman, 2019). A further application was e-Kanban, which allowed better communication between the warehouse and the shop floor, thus helping to improve the scheduling system, which reduced delays (Phumchusri and Panyavai, 2015).

Additionally, training has been a vital part of the success in some case studies, as it was also considered a pre-condition (Ab Rashid *et al.*, 2015; Antosz and Pacana, 2018). Industry 4.0 tools need to be managed by experts in the system (Ito *et al.*, 2020) and further used by trained people to make sure that the correct procedure is followed. Research done by Srinivasan *et al.* (2020) highlighted that employees that use Industry 4.0 need to be equipped with five types of skills: technical, problem-solving, social, cognitive, communication, and personal. Skillset and capability play a major role in the success of implementation to ensure full benefit is achieved from the application. In addition to increased implementation success, training enhances employees' capability to sustain improvements (Azouz and Pierreval, 2019).

Overall, the success of implementation lies in social dimensions relating to skills, training, and communication between employees and top management. Hence, managers need to acknowledge these factors, lead their employees through the implementation, invest in their communication, and upskill them where necessary. Employees are the decisive point of success in the implementation, so an option would be to have an assessment of their team’s readiness in terms of skills, communication, and leadership abilities before supporting an initiative. As this study and previous research show, employees who cannot communicate effectively, lack leadership, lack the right digital literacy, or lack basic knowledge of Lean are unlikely to lead a successful application (Knol *et al.*, 2018; Moeuf *et al.*, 2020a). In another effort to improve the success rate, wider company measures can be taken, such as adapting the HR strategy to recruit a multi-skilled and digitally literate workforce (Ghobakhloo and Fathi, 2020)

4.6 *Barriers* - What are the barriers to the integration of lean manufacturing principles with Industry 4.0?

There are two types of barriers identified in this study. The first type was the barriers that arise from challenges due to the integration. The second is the inherited barriers; these are individual challenges that are related to Lean and Industry 4.0 and are still present in the application of the integration.

One of the inherited barriers for both paradigms is the cost of implementation. In an interview-based research conducted by Müller, Buliga and Voigt (2018), 68 German SMEs identified the cost of investment, IT infrastructure, and training as the challenges attached to the implementation of Industry 4.0. In the same study, the investment cost of implementing CPS in one of the SMEs was identified as €2,000 per machine, resulting in a total investment of €360,000. However, the cost of investment is not the only inherited barrier of Industry 4.0; technological readiness, privacy concerns, and use of systems were also challenges that were not eliminated or alleviated by the inclusion of Lean.

Like Industry 4.0, Lean is also considered a costly and risky investment, so convincing management is challenging (Alzubi *et al.*, 2019). In case studies, possible improvements presented by Lean principles required investments such as acquiring new equipment and hiring employees (Ab Rashid *et al.*, 2015; Alvandi *et al.*, 2016). To overcome this barrier, the benefits of investment along the payback period have been conveyed to management to increase the chance of support (Parthanadee and Buddhakulsomsiri, 2014; Ab Rashid *et al.*, 2015). Overall, high cost has been identified as a reason for the loss of management support thus disabling a possible application (Dhiravidamani *et al.*, 2018). Along with a lack of management support, employees' resistance to change is also mentioned as a barrier to implementation (Erkayman, 2019).

Effects on the environment can be a possible inherited barrier of Lean affecting the integration, as certain trade-offs are observed in the implementation that leads to certain disadvantages in terms of CO_2 emissions and resource use (Alvandi *et al.*, 2016). From a broader perspective, implementation of lean principles has led to higher throughput and shorter lead-times, requiring increased material and other resources in a shorter amount of time. Furthermore, implementation of JIT has been shown to have negative implications for the environment (Sartal, Martinez-Senra and Cruz-Machado, 2018). This argument is supported by research conducted by Dieste *et al.* (2019), which showed that 14% of the 72 papers analysed revealed both the positive and negative impacts of Lean implementation on the environment.

In terms of barriers that arise due to integration, these include technological suitability and resistance. Furthermore, according to Liker (2020), only the technology that supports people and processes can be effectively incorporated into Lean. As lean principles resist the inclusion of technology that does not serve employees or the operations, technological suitability becomes a barrier to integration. An example of this was observed in a case study by Boudella, Sahin and Dallery (2018), where automation was introduced to a JIT production to trial a hybrid robot-human kitting system. The hybrid system was constructed considering the operator and system needs. However, the trial concluded that some criteria relating to floor space and part characteristics needed to be satisfied further before full adoption of the automation system could be considered.

Another unique challenge that arises is about the management of the implementation process. Often, digitisation and lean initiatives involve different teams in the same facility with different objectives; one focuses on improvements and the other on digitisation. The lack of unified objectives could risk the application's success, as it disengages the vertical integration objective set out by Industry 4.0.

Overall, the main barriers in the reviewed case studies were related to the cost of investment, technological readiness, lack of management support, and resistance to change, which were also identified in previous research focusing on individual implementation (Jadhav, Mantha and Rane, 2014; Horváth and Szabó, 2019). Cost of investment is the most prevalent barrier, where it is important to consider that many initiatives may not even start because integration is seen as risky and costly (Atieh *et al.*, 2016; Alzubi *et al.*, 2019). On the other hand, the failure rate and the efforts attached to the project are sufficient to repel managers who will be responsible for any potential failure (Zwikael and Globerson, 2006). In addition, Lean and Industry 4.0 provide a long-term benefit where the rate of return on investment could be long term, which can affect the decisions of managers, who tend to be too concerned about the short-term return of benefit (Nazarov and Klarin, 2020). To overcome these barriers, government incentives and reduction in the cost of digital tools like sensors play an important role, as the reduced cost of sensors is one of the causes of the widespread digitisation fuelling Industry 4.0. Additionally, visualising potential benefits and application scenarios could play an important role in convincing top management to support implementation (Lugert and Winkler, 2019). Similarly, problems regarding social aspects, such as resistance to change, can also be solved through showing the potential benefits of the integration, such as improved employee welfare and better decision making. It is also important to note that some inherited barriers, such as security concerns, were not mentioned in the case studies.

5 Theoretical, Managerial and Practical Contributions

In terms of theoretical contributions, this is the first study that systematically reviews case studies that combine Lean and Industry 4.0, incorporating economic, environmental, and social aspects. This approach derived from TBL makes it possible to display a complete assessment of the effects of integration. As the previous studies have focused only on economic aspects, this study fills the gap in the theoretical literature by introducing social and environmental aspects and by exploring how some aspects can be integrated into applications. Secondly, by determining the success factors, barriers, and benefits of integrating Lean and Industry 4.0, this research contributes to the literature by analysing the determinants and outcomes of the integration in real case studies. This introduces a new analysis of the social and environmental dimensions as well as extending the knowledge in operational excellence. Thirdly, the study investigates the order in which Lean and Industry 4.0 were applied in the case studies. Theoretical research has been mostly focused on applying Lean first (Bortolotti and Romano, 2012; Prinz, Kreggenfeld and Kuhlenkötter, 2018), but this study introduces the potential of Industry 4.0 first application in practice. Finally, this study aimed to identify the barriers specific to the integration and to guide future research to enable the successful implementation of Lean and Industry 4.0.

One of the main managerial contributions of this study is introducing the success factors and barriers to Lean and Industry 4.0 integration. It enables managers to prepare themselves for any potential hindrance and to improve the chance of success. For example, where the cost of investment is a barrier, a manager can recognise it and use tools such as VSM and simulation to show the potential improvement to convince the leadership of which important success factor to enhance. Further, a manager can encourage teamworking skills between the improvement and digitisation teams in a plant, having identified the unique barrier arising through integration. Additionally, through recognising the potential benefits of the integration in different contexts, such as environmental and social, the support of different target groups can be gained. For example, showing improved welfare will gain the support of the shopfloor. Similarly, the environmental benefit gained through effective resource use will gain the support of the public.

Another important outcome of this study was to demonstrate that the combination of Lean and Industry 4.0 is not necessarily a costly method. Many case studies used VSM and simulation, which required just the relevant software and a value stream map of the process (Stump and Badurdeen, 2012; Bait, di Pietro and Schiraldi, 2020). This allows managers to consider using this integrated approach without worrying about cost or convincing upper leadership about investment. This method allows another benefit for managers in that it offers increased decision making through a display of the process of the flow and effect of adopting different scenarios (Helleno *et al.*, 2015). Further, the importance of training and digital literacy in the future would help managers to prepare themselves and their team. It would also encourage HR to define training programs and adapt their hiring policy to consider these digital skills.

In terms of practical implications regarding the environmental benefits, this study showed that Industry 4.0 and Lean applications allowed manufacturing companies to be more considerate and make more informed decisions toward the environment. As seen in Alvandi *et al. (*2016), when faced with an option to replace machinery, the company calculated the environmental impact of using an electric or gas version before making a final decision. When it comes to any process that uses resources, Lean can create awareness for wasteful resources. This combined with resource use data that can be acquired, processed, and analysed through Industry 4.0 tools, can help manufacturing companies be aware of their environmental impact. As a further step, the self-optimisation feature of Industry 4.0 together can help create solutions for companies to better tailor their production sequences, resources, and machinery used to benefit the environment.

In technological perspective, one of the implications is that Lean can be a driver for technological advancement in the manufacturing context and beyond. The examples of this drive started since the beginning where Jidoka's aim for defect-free production. In this context, advancement in technology first led to automation and further early diagnosis of errors through data acquisition analysis capability of Industry 4.0. The need for Lean tools to be used more effectively and with less complications have given momentum to the evolution of technology which dissipated to other sectors. As another example, various case studies have shown the evolution of Kanban to E-Kanban where human errors and lost cards in the manual system led to the use and evolution of electronic signalling (Pekarcikova et al., 2020). The E-Kanban concept has even benefitted the project management industry, where a Kanban software has been developed to manage projects, workflow and teams (Gould, 2018; Kanbanize, 2021). Simulation was integrated with VSM to make it more dynamic, which transferred into the digital twins concept, a virtual representation that can do iterative optimisation (Tao et al., 2019). Hence, improving Lean practices and aiming for more efficiency is one of the ways to enhance digital tools and applications.

In terms of social implications, the implementation of Lean and Industry 4.0 created a need for advanced communication between people and Industry 4.0 tools. To achieve this, employees need to be provided with the necessary digital tools training and digital literacy to begin with (BMAS, 2015). The governments and policymakers need to provide required infrastructure and training, especially for SMEs, to accelerate upskilling and reskilling of workers in preparedness for Industry 4.0 implementation. Further, providing everyone with equal access and filling the existing gap on digital knowledge are also other aspects to be considered. The era of Industry 4.0 also puts pressure on academic institutions to revise their program offerings to ensure graduates have the required technical and soft skills to embrace Industry 4.0 technologies. The software and hardware companies can design interfaces and physical tools simpler and more user-friendly to enhance communication. Indeed, there will be job losses, especially where automation/AI/ML can replace standard work but at the same time, thousands of other types of skilled jobs will be created. Therefore, the need for knowledge workers will be even greater in the era of Industry 4.0.

This study also showed that all three aspects of TBL and their interrelation need to be considered before applying Lean and Industry 4.0. This can be explained in an example starting from a social factor, where the resistance to change or lack of contribution from employees can unintentionally sabotage a project, as mentioned by Worley and Doolen (2006). This could lead to losing investments made by the company and loss of economic and environmental resources. Similarly, while decisions on machinery and power might have trade-offs, choosing environmentally friendlier options could be more expensive. Thus, companies need to analyse the impact of all these aspects and their effect on others to prepare for applications.

6 Conclusion

This study aimed to analyse the systematic review of case studies that combine lean principles and Industry 4.0 in manufacturing plants. Overall, an extensive range of lean principles and Industry 4.0 tools have been captured in the case studies analysed through this review. However, much of the focus has been on VSM and simulation due to their cost effectiveness, adaptability, and function. The order of application in the case studies has been varied where Lean was applied first, last, and simultaneously with Industry 4.0 depending on the company's aim and existing resources.

A wide range of benefits has been identified through the combined application of Lean and Industry 4.0, which indicates an important potential benefit for its future implementation. Substantial improvements in lead-time, cost, and quality were reported. Operational benefits, such as reduction of defects and reworking have improved the performance and helped the environment. In terms of further environmental benefits, the use of resources was measured, which brought awareness of the decision implications. Social benefits focused on employees, and success factors mostly stemmed from social aspects, such as employee participation and training. Some of the barriers of the application arise from the integration, and some, like cost, technological readiness, and environmental concerns, are inherited by Lean and Industry 4.0.

7 Future Research

The future research can be categorised into four main topics related to the implementation of Lean and Industry 4.0 and their environmental and social benefits.

There is a gap in the literature focusing on Industry 4.0's first and simultaneous application with Lean. Most of the research focuses on Lean leading the integration; however, this study shows that the order of application can depend on other variables, such as a company's aim and existing resources. This aspect needs to be researched further.

There is limited research on the use of Lean and Industry 4.0 for environmental benefits. This study demonstrated that environmental gains were limited to resource consumption. The scope of this research can be expanded so that renewable energy and recycling can be linked with Lean and Industry 4.0 in future studies.

There is limited focus on the social benefits of Lean and Industry 4.0 implementation, although social factors build the foundations of the application's success. Future research can focus on the development of social dimensions and how people and the workforce can be employed to further improve the application's success and improve social welfare.

The use of advanced Industry 4.0 tools, such as Digital Twin, AI, CPS, and IoT, can be increased in the manufacturing field to analyse this integration in a more advanced setting. Currently, the application mainly focuses on relatively simple tools like simulation.

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