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Industry 4.0 and Lean Manufacturing - A systematic review of the state of the art literature and key recommendations for future research

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Industry 4.0 and Lean Manufacturing - A systematic review of the state-of-the-art literature and key recommendations for future research

Abstract

Purpose – This paper aims to analyse the current state of research to identify the link between Lean Manufacturing and Industry 4.0 (I4.0) technologies to map out different research themes, to uncover research gaps, and propose key recommendations for future research, including lessons to be learnt from the integration of lean and I4.0.

Study design/methodology/approach – A systematic literature review (SLR) is conducted to thematically analyse and synthesise existing literature on Lean Manufacturing - I4.0 integration. The review analysed 60 papers in peer-reviewed journals.

Findings – In total, five main research themes were identified, and a thematic map was created to explore the following: (1) The Relationship between Lean Manufacturing and I4.0, (2) Lean Manufacturing and I4.0 implication on performance, (3) Lean Manufacturing and I4.0 framework, (4) Lean Manufacturing and I4.0 integration with other methodologies, and (5) Application of I4.0 technologies in Lean Manufacturing. Further, various gaps in the literature were identified, and key recommendations for future directions were proposed.

Research Implications -
The integration of Lean Manufacturing and I4.0 will eventually bring many benefits and offers superior and long-term competitive advantages. This research reveals the need for more analysis to thoroughly examine how this can be achieved in real life and promote operational changes that ensure enterprises run more sustainably.

Originality/value – The development of Lean Manufacturing and I4.0 integration is still in its infancy, with most articles in this field published in the last two years. The five main research themes identified through thematic synthesis are provided in the original contribution. This provides scholars better insight into the existing literature related to Lean Manufacturing and I4.0, further contributing to defining clear topics for future research opportunities. It also has important implications for industrialists, who can develop more profound and richer knowledge than Lean and I4.0, which would, in turn, help them develop more effective deployment strategies and have a positive commercial impact.

Keywords Lean Manufacturing, Industry 4.0, Systematic literature review

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1. Introduction

Lean manufacturing was developed during the third industrial revolution as a management philosophy that focuses on improving the organisation's efficiency, as implemented across different sectors of industries (Tayaksi *et al*., 2020). The goal of Lean Manufacturing is to eliminate all types of waste, focusing on the activities that add value to the customer (Womack and Jones, 2003). Lean manufacturing can be defined as "an innovative paradigm that eliminates waste in any form, anywhere and at any time, relentlessly strives to maintain harmony in the flow of materials and information, and continually attempts to attain perfection" (Mohanty *et al*., 2007). Lean manufacturing is also associated with people's development and the creation of problem-solving culture by engaging and involving everyone in tackling some problems through experiential learning from practical countermeasures (Ballé *et al*., 2019). Lean manufacturing is a set of practices and principles that enables organisations to coordinate and support production. It is one such methodology that can significantly improve quality, reduce cost, reduce lead time, and improve the firm's productivity (Sanchez and Pérez, 2001). In recent decades, with the advancement of information and communication technology (ICT), numerous studies have been conducted to investigate how the integration of lean manufacturing and ICT can achieve better performance (e.g., Houy, 2005; Maguire, 2016). The evidence shows that because of this integration, hybrid solutions such as enterprise resource planning (ERP) and manufacturing execution systems (MES); have been built to support many companies to successfully transform into lean companies (Buer *et al*., 2018). Nevertheless, after the advent of the fourth industrial revolution, the trend has slowly shifted, where lean manufacturing in the I4.0 environment is now gaining attention from researchers. Since both have similar objectives of higher productivity, reduced cost, and improved quality but are relatively different in their application (Buer *et al*., 2018; Pagliosa *et al*., 2019). Lean Manufacturing is straightforward, uses traditional methods, and is more human-centric with employee empowerment (Pagliosa *et al*., 2019). On the contrary, I4.0 utilises the latest technology, is more advanced, and aims at higher automation with less human interface. In addition, since the early 1990s, the first attempts to integrate automation technology into lean manufacturing emerged under lean automation. Lean automation is expected to respond to future market demands by increasing changeability and shortening information flows (Tortorella *et al*., 2020a). However, its application to date has been limited primarily due to technological capabilities (Kolberg and Zühlke, 2015). Given the potential of I4.0 technologies, there are new fields of application for lean automation to enhance performance (Tortorella *et al*., 2020a). For instance, the new advanced analytics technologies incorporated in I4.0 technologies, such as Machine Learning and Big Data, can detect system-wide issues or untapped potential in real-time and automate the continuous improvement process (Gupta *et al*., 2020). According to Dombrowski *et al*. (2017), equipping machines with advanced analytics technologies makes them self-aware and self-maintaining, which can significantly improve their total productive and preventative maintenance.

A few systematic literature reviews have been conducted on Lean Manufacturing and I4.0 integration and yielded some interesting insights. They have primarily focused on identifying the relationship between Lean Manufacturing and I4.0 to see how this integration can reap benefits from digital technology advancement and organisational process improvement. For example, as the first systematic literature review in this area, Buer *et al*. (2018) performed a state-of-the-art analysis of the Lean Manufacturing and I4.0 literature, particularly interested in how I4.0 technologies can support lean manufacturing practices and vice versa. In addition, the authors investigated whether the integration of lean manufacturing and I4.0 can connect

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with performance implications and environmental factors. Pagliosa *et al.* (2019) focused on identifying the relationships between I4.0 technologies and lean manufacturing practices and concluded that there is a positive interaction and synergy between them to achieve higher operational performance. In a more recent study, Bittencourt *et al.* (2021) investigated how lean thinking can trigger I4.0 implementation. They stated that Lean concepts (i.e., work standardisation, organisation and transparency) are crucial for I4.0 implementation.

Although after the advent of I4.0, many scholars tried to identify the relationship between Lean Manufacturing and I4., other aspects have emerged that have been rarely covered by the previous reviews. For example, researchers with diverse interests have started to develop frameworks for integrating lean manufacturing and I4.0 technologies (e.g., Pozzi *et al.,* 2021; Abd Rahman *et al.*, 2021). Several studies have argued that lean manufacturing-I4.0 integration is insufficient and that integration with other methods is necessary (e.g., Leong *et al.*, 2020; Amjad *et al.*, 2021). Some scholars have also demonstrated how specific I4.0 technologies can integrate with lean tools (e.g., Ito *et al.,* 2020; Tortorella *et al.*, 2021). Furthermore, authors have investigated the impact of integrating I4.0 and lean manufacturing on different aspects of enterprise performance (e.g., Kamble *et al.*, 2020).

Hence, to contribute to this discussion and facilitate further research, these observations motivated us to conduct a state-of-the-art analysis of the existing contributions on this emerging subject. The analysis aims to map out research themes on the integration of "Lean Manufacturing" and "I4.0 technologies", uncovering research gaps and proposing key recommendations for future research. This is also a significant area to be looked at by scholars and practitioners as Industry 4.0 sets the scene for continuous improvement, one of the lean principles and organisation performance improvement. The considerable amount of data generated from I4.0 is essential for lean implementation as it is a data-driven philosophy. Therefore, the integration between both Lean and I4.0 is a significant area for research by scholars and practitioners to develop a deeper understanding of the relationship between both; hence, developing more effective deployment strategies.

Therefore, the main research questions (RQ) addressed in this study are as follows:

RQ1. What are the emerging themes in research on integrating Lean Manufacturing and I4.0?

RQ2. What are the key recommendations for future research on integrating Lean Manufacturing and I4.0?

The remainder of the paper is organised as follows: in the next section, a background on Industry 4.0 and a brief description of its technologies are provided. Section 2 describes the research methodology; Section 3 outlines the main findings of the different research streams. Section 4 offers the key recommendations for further research. Then, the paper ends with overall conclusions, highlighting the commercial impact of lean and I4.0 integration and industrial society's awareness of the application of digital technologies in lean organisations,

1.1. Industry 4.0 background

To date, we have experienced four industrial revolutions characterised by technological shifts. The first revolution consisted of mechanisation, the second revolution was driven by assembly lines focused on mass production systems, and the third revolution was characterised by automation and computers. The first three revolutions spanned nearly 200 years, and now we

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are in the fourth revolution. I4.0 stems from the German equivalent "Industrie 4.0", introduced at the Hannover Fair of 2011, which is the application of cyber-physical systems in industries, allowing real-time integration while making the value chain more productive, intelligent, and agile (Pagliosa *et al.,* 2019). I4.0 promotes the customisation of products and services, improving profitability, and having a key focus on process automation (Schmidt *et al.*, 2015). Enabling the machines to be self-conscious and with self-learning, platforms become more efficient. The smart factories will be able to track production status with real-time data monitoring and maintain instructions for monitoring production processes (Valamede *et al.,* 2020). I4.0 is mainly driven by data, which has also led to tremendous growth in the data across every business and industry sector (Abd Rahman *et al.,* 2021). As different authors have different definitions for I4.0, there is no consensus in the classification of the various I4.0 technologies (Rosin *et al.,*2020), and the authors have described a list of technologies with a slight difference in their research work. Table I demonstrates a brief description of notable I4.0 technologies from the literature.

[**Table I** *near here*]

2. Research methodology

An SLR is a methodology that identifies the existing work done by researchers then selects and assesses the contribution from various researchers; analyses and synthesises the data and produces the results in such a way that there is a clear summary of what is known and what is not (Denyer and Tranfield, 2009). An SLR also forms a base for future research, promotes theory development, aligns the existing research, and discovers areas where additional research can be carried out (Webster and Watson, 2002).

Cook *et al*. (1997) stated that the Systematic Literature Review (SLR) methodology has been used for the first time in medical research to enhance the quality of the review process and increase confidence in the research findings to create new directions in research or/and establish new valid policies. In addition, SLR provides a comprehensive search for existing evidence by synthesising the results. Due to the nature of this study's research aim, SLR was chosen as an appropriate research methodology.

Hence, this study follows five typical SLR steps as proposed by (Denyer and Tranfield, 2009), consisting of 1) question formulation; 2) locating studies; 3) study selection and evaluation; 4) analysis and synthesis, and 5) reporting and using the results which are widely accepted in the literature. The steps are laid out in a well-structured manner, with the first step asking framed questions. The next step is identifying the relevant work in the field, and selecting the relevant work using established criteria. The shortlisted work is then further broken down and described to show how they are related and contribute to the work. Finally, a summary is provided based on the overall analysis of the contribution, and a conclusion has arrived at for the research question. The first and fifth phases are reported in section 1 and section 3 of this paper, respectively, while phases two, three and four are discussed in the following sub-sections. The overall strategy carried out in the systematic literature review is shown in figure 1, consisting of five steps with results and the purpose of each step.

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The screening, inclusion/exclusion, analysis and synthesis of the relevant articles have been carried out by a research team of three academics and a research student. Table II provides detail of the research team involved in this research with their expertise and responsibility towards this article.

[**Table II** *near here*]

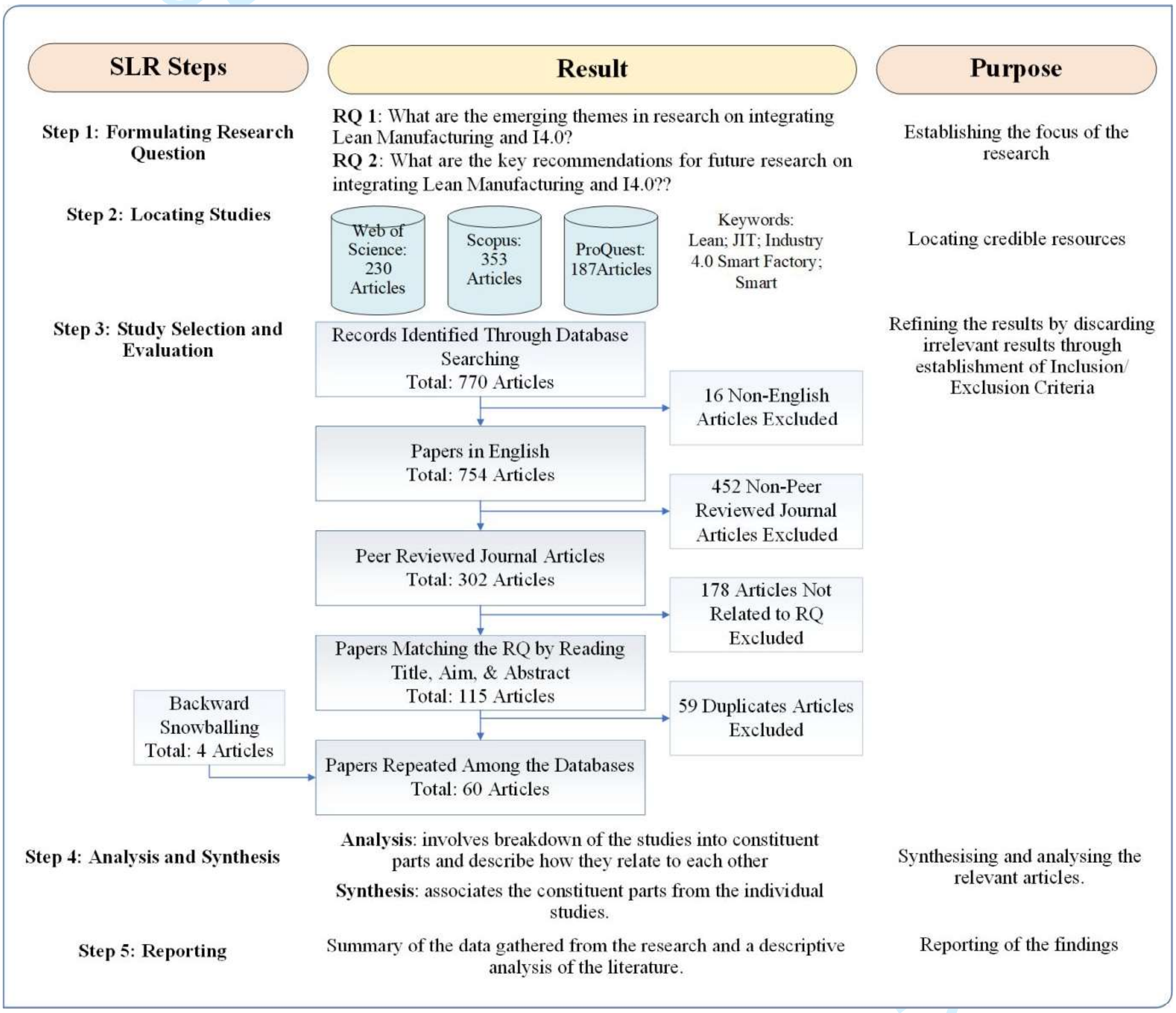

Figure 1. Systematic Literature Review Strategy

2.1. Location of studies and selection

This step involves locating the relevant research to the research questions (RQ). This is a vital step; if the selected literature is inappropriate or inadequate, then there will not be credit for further steps (Sangwa and Sangwan, 2018). This phase consists of two stages: choice of the search engine and choice of search word strings (Denyer and Tranfield, 2009). The choice of web search engines was not used to avoid information noise. To locate the relevant research, Web of Science, Scopus, and ProQuest databases were used. Using more than one database reduces the possibility of missing all pertinent research and any Publication Bias. The search strings have been designed with appropriate keywords such that the result reflects the RQ framework. The search strings were constructed using Boolean operators to give optimum outcomes (see Table III). This ensured that the results from each search would comprise of the keywords desired either in the Title, Abstract, or the Research paper's Keywords. As every database has its own way of defining the search strings, these were carefully constructed for individual databases and the results were cross confirmed by primarily reading the abstracts of the selected results. A total of 770 papers under Lean Manufacturing-I4.0 were identified from 2011 when the I4.0 was introduced to the first half of 2021, with the highest contribution of 353 papers from Scopus, followed by 230 papers from Web of Science and 187 papers from ProQuest.

[**Table III** *near here*]

2.2. Study selection and evaluation

This step aims to refine the identified results by discarding the irrelevant ones. This is achieved by defining a criterion to select the relevant research and eliminate the remaining results to see if it addresses the RQ (Denyer and Tranfield, 2009). This involves recording the decisions of which results were included or excluded. As shown in figure 1, the search was first limited to work published in English, and others were discarded. The search was also restricted to peer-reviewed journal articles and articles in press that would be later published in 2021. Then, the remaining results' title, aim and abstract were carefully studied, and irrelevant studies were disregarded. When a conclusion was not achieved by reading the abstract, the theoretical framework, results, and conclusion were reviewed to make the final decision. Finally, as three databases were used, duplication of the article was checked by keeping Web of Science as the base and comparing it with Scopus and ProQuest. A final sample of 60 articles relevant to Lean Manufacturing and I4.0 was identified and uploaded to QSR NVivo 12 software. QSR NVivo, along with data extraction forms, was also used to perform a thematic synthesis due to its capability to encode data from complete articles (Garza-Reyes, 2015).

2.3. Analysis and synthesis

The Analysis stage aims to break down the studies into constituent parts and describe how they relate. The Synthesis stage seeks to associate the constituent parts from the individual studies (Denyer and Tranfield, 2009). In the analysis stage, information must be extracted and stored in the data extraction forms, which is done by using specifically framed questions. The questions adapted for the data extraction form were general details, including: (Author, Title, Date, Journal), type of study, aim and objective, key findings, relevance, and the number of times the paper has been cited. A thematic analysis approach is considered for synthesising the qualitative research. A thematic analysis approach consists of a structured way of using the data within each theme. It is considered the most suitable method for consolidating the data obtained from a systematic literature review (Garza-Reyes, 2015). An initial classification of

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the selected articles was done based on the type of research methodology adopted, and five groups were formed (see Section 3.1). This initial classification made it possible to codify and analyse 60 articles individually, assign them to one of the classification groups and then compare them with articles in other categories. After that, new classifications were made based on the previous classification and coding, which eventually led to a thematic map (see figure 7) showing the different research streams pursued by the Lean Manufacturing-I4.0 subject area. The findings of the thematic synthesis are discussed in the next section.

3. Findings and discussion

3.1. Bibliometric analysis

Out of a total number of 60 papers under the Lean Manufacturing-I4.0 topic, which were shortlisted, the first paper was published in 2014. Since then, there has been a continuous rise in the number of publications depicting the interest of researchers and academicians in this area. Figure 2 shows the increasing trend of publications from the year 2014, with the highest number of publications of 28 in the year 2020 and 13 publications already in the first half of 2021.

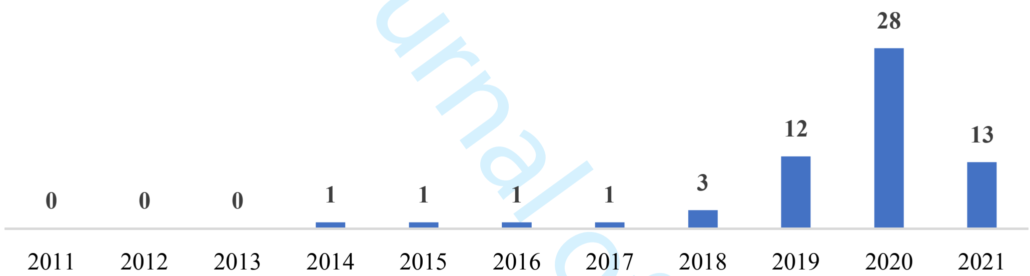

Figure 2. Number of Publications per year under Lean Manufacturing-I4.0 integration topic

The publications start from the year 2014, where the publications from the years 2020 and 2021 contribute to 68% of the publications, depicting that it is an emerging topic. The number of citations is also an increasing trend, with 36.7% of the papers cited more than five times, 41.7% of the papers cited less than five times, and 21.7% of the papers were never cited. The most cited papers were (Guo *et al.*, 2015), with 197 cites, (Sanders *et al.*, 2016), with 157 cites, (Fettermann and Tortorella, 2018) with 130 cites, (Buer *et al.,* 2018), with 116 cites, and (Rossini *et al.,* 2019) with 76 cites.

As shown in Table IV, an initial analysis of the articles was done based on the type of research methodology adopted, and five groups were formed:

- Literature Review (LR),
- Survey (Interviews),
- Case Study,
- Conceptual papers and
- Mixed methods

In the selected articles, the case study approach dominated among others with 23 articles, with specific application of the developed model in an industrial case study, followed by surveys and interviews with 18 articles. The research proposal was evaluated through interviews and surveys/questionnaires with industrial experts. Other researchers used a conceptual approach through LR with 12 articles and conceptual papers with four articles to present their research

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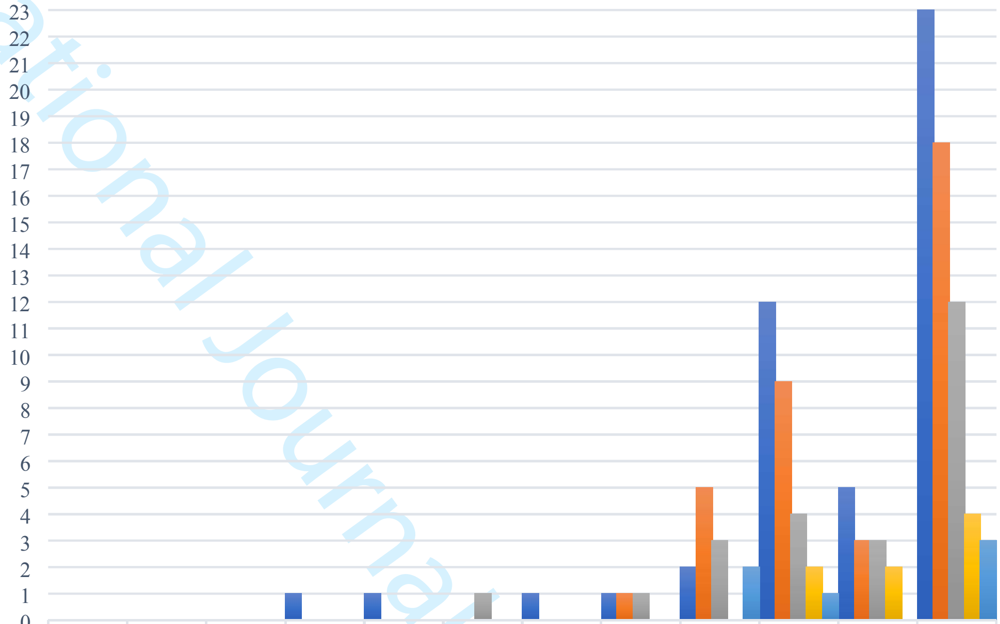
findings. There were three articles where mixed methods were used with a combination of 'LR and Survey' consisting of one paper, and 'Survey and Case Study with two papers. The number of publications per year that were classified according to every group is shown in Figure 3.

[**Table IV** *near here*]



	m	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	Total
Case Study	0	0	0	1	1	0	1	1	2	12	5	23
Survey	0	0	0	0	0	0	0	1	5	9	3	18
LR	0	0	0	0	0	1	0	1	3	4	3	12
Conceptual Study	0	0	0	0	0	0	0	0	0	2	2	4
Mixed methods	0	0	0	0	0	0	0	0	2	1	0	3

Figure 3. Number of Publications per year based on the research methodologies in the investigated articles

Concerning the contribution of Journals, the 'International Journal of Production Research' had the highest number of publications with eight papers, followed by 'Production Planning and Control' and 'Sensors' with five publications each, and 'TQM Journal', 'Journal of Manufacturing Technology Management' and 'Sustainability' with three publications each, as depicted in figure 4.

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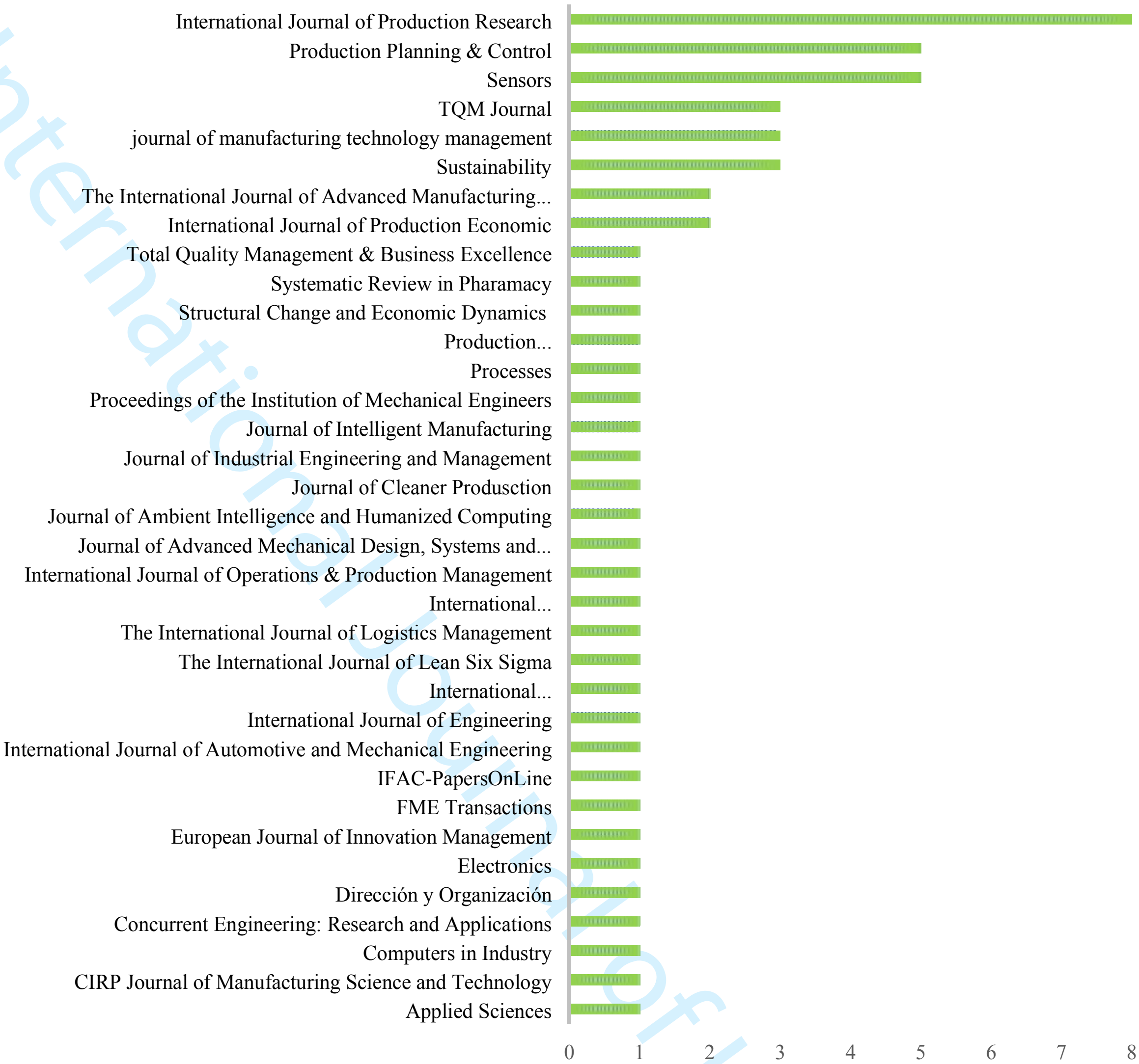

Figure 4. Number of publications in Journals under Lean Manufacturing-I4.0 integration topic

When the shortlisted papers were filtered from the country of origin (where the research has been conducted), Italy was the country to contribute highest with nine papers, followed by Brazil with eight papers, and India and UK with five papers each. The world map representing the contribution of research articles from each country is shown in figure 5, classifications are provided based on the number of research articles per country. The contribution to the research from a developed country was 55% and from developing countries was 45%. This signifies that even developing economies have shown tremendous interest in the field and have tried to adopt the latest technology. Globalisation has also been effective, as the companies from the developing economies have expanded globally with affiliate companies all over the world, contributing to the development of the manufacturing sector in developing countries.

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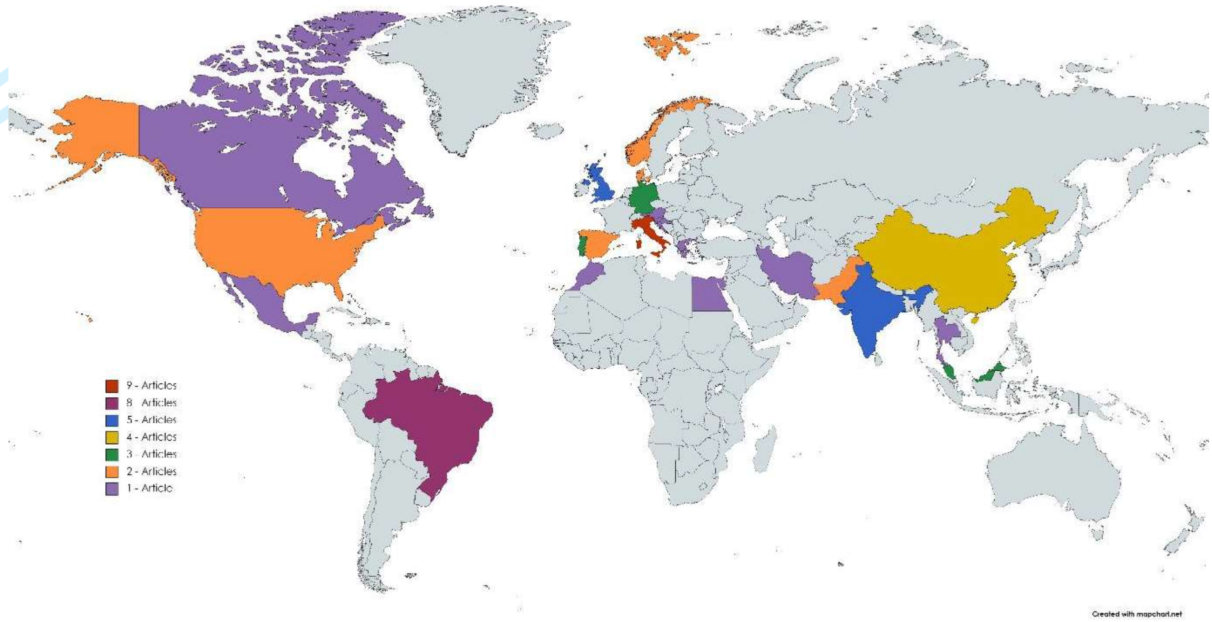
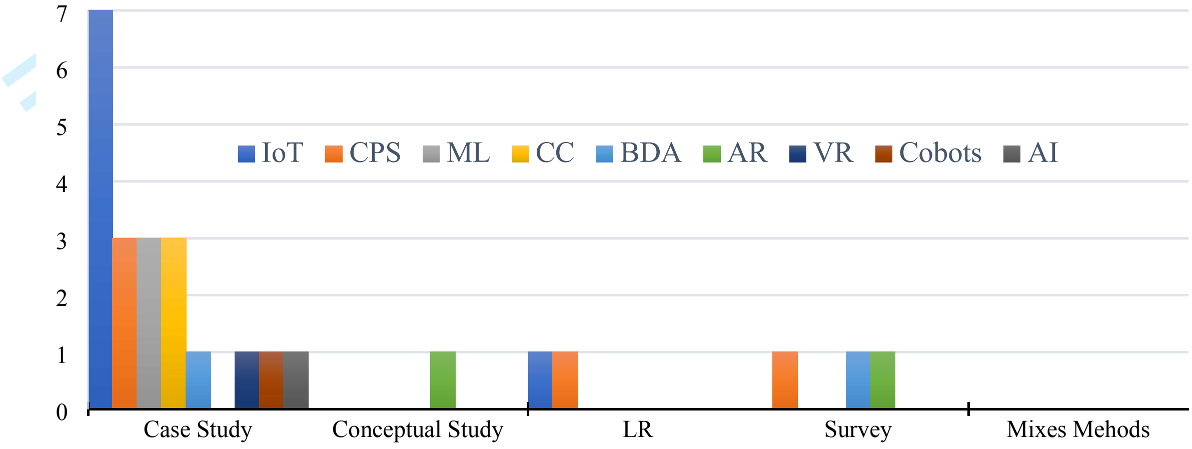
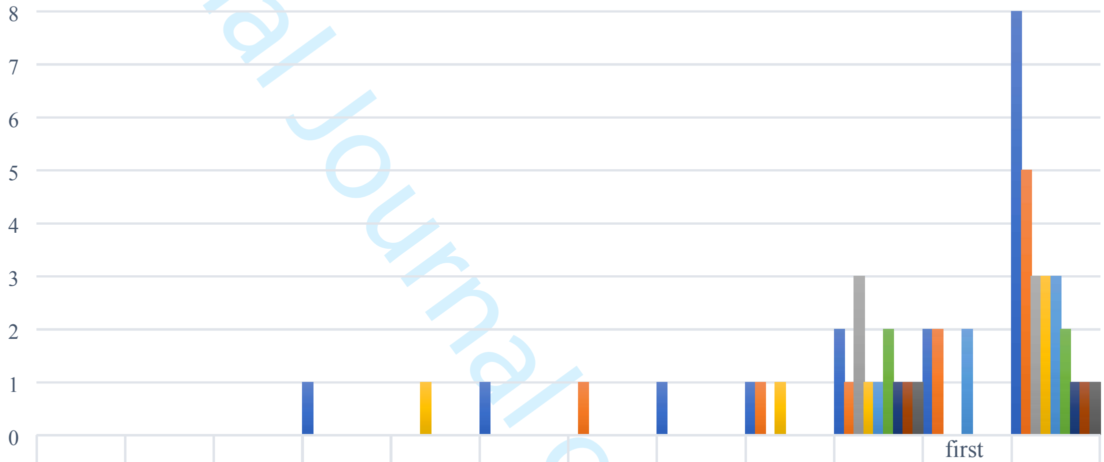


Figure 5. World map representing the contribution of articles under Lean Manufacturing-I4.0 integration topic.

As demonstrated in Figure 6, on analysing the application of the technology in the research papers, nine I4.0 technologies were identified, which were mostly quoted in the most recent articles that utilised case studies as the research method., In addition, the results depicted that Internet of Things (IoT) technology was the highest quoted by authors with eight papers, followed by Cyber-Physical System (CPS) with five papers, Machine Learning (ML), Big Data Analytics (BDA), and Cloud Computing (CC) were quoted in three papers each, and the remaining technologies were discussed in at least one paper each. The high citation frequency of IoT was mainly because IoT acts as a base for other technologies such as CPS, CC, etc. (Tamás *et al.,* 2016). The advancement of technology, accessibility, and the low cost of the internet has also led to its prominence. CPS is associated with smart devices/sensors in the equipment, which is capable of transmitting information and has found applications in smart factories and digitalisation. ML is mainly linked with the automation aspect, and as most companies are going towards automation, ML has gained importance in improving process performance. BDA is a handy tool, especially in predicting from a large volume of data and supporting the manager in taking decisions. CC also supports the decision support system by utilising cloud technology to store and retrieve the data and mainly helps in real-time monitoring. Other technologies, such as Artificial Intelligence (AI) and Collaborative Robots (Cobots), have applications in the manufacturing sector. Still, due to the current development of the technology, the application is comparatively less.



(a)



	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	first half of 2021	Total
IoT	0	0	0	1	0	1	0	1	1	2	2	8
CPS	0	0	0	0	0	0	1	0	1	1	2	5
ML	0	0	0	0	0	0	0	0	0	3	0	3
CC	0	0	0	0	1	0	0	0	1	1	0	3
BDA	0	0	0	0	0	0	0	0	0	1	2	3
AR	0	0	0	0	0	0	0	0	0	2	0	2
VR	0	0	0	0	0	0	0	0	0	1	0	1
Cobots	0	0	0	0	0	0	0	0	0	1	0	1
AI	0	0	0	0	0	0	0	0	0	1	0	1

(b)

Figure 6. I4.0 technology with citations in the identified research paper based on the methodology type (a) and the publication year (b) under the Lean Manufacturing-I4.0 integration subject area

3.2. Themes and sub-themes for Lean Manufacturing and I4.0 technologies

While all the shortlisted articles (60) represent the relationship between Lean Manufacturing and I4.0 technologies, as depicted in Table IV, they have different approaches to addressing the topic. Hence, as illustrated in figure 7, a thematic map was created inductively to organise, categorise, and structure the results obtained from the SLR. In addition, the relevant articles

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were attached for each identified theme and/or sub-theme, which depict where Lean Manufacturing -I4.0 research had been focused and where it has been limited. All the articles fell into either of the identified themes, whereas some identified articles represented more than one theme. These themes are discussed in sections 3.2.1 to 3.2.5.

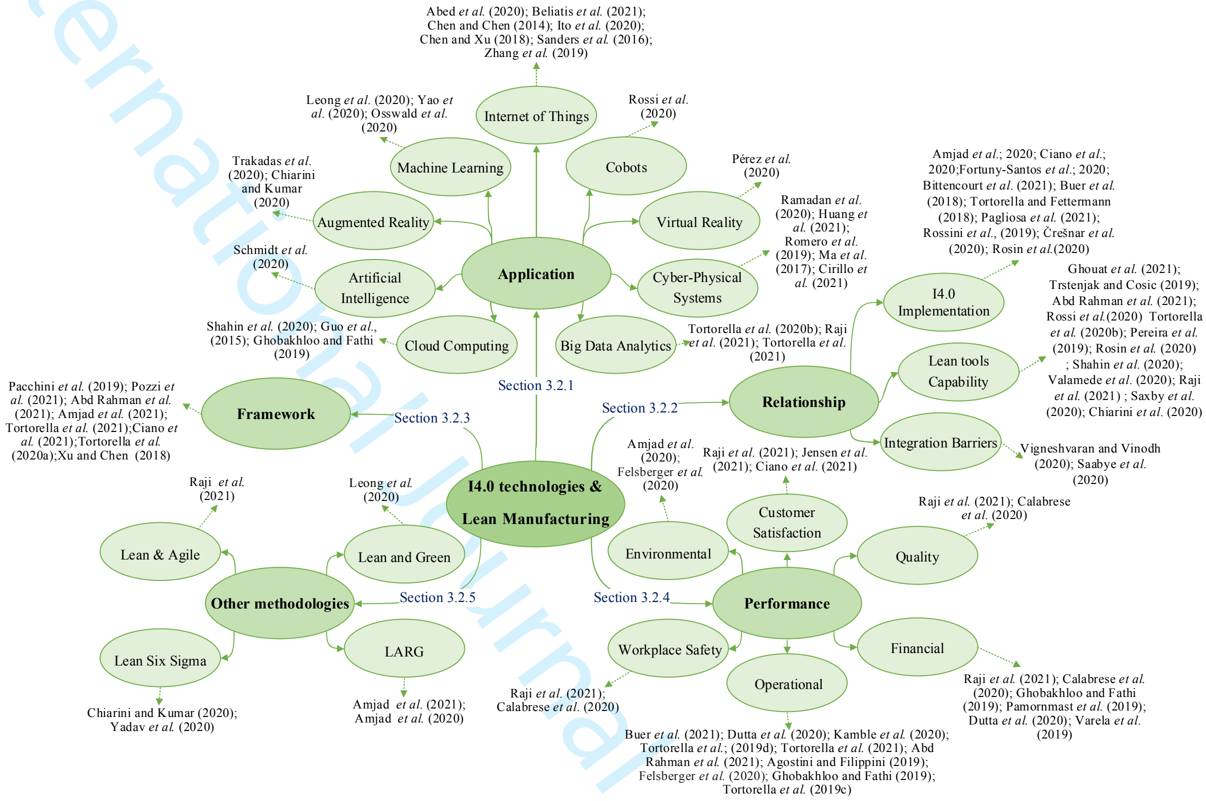

Figure 7. Thematic analysis of Lean Manufacturing- I4.0 integration literature review

3.2.1. Relationship between Lean Manufacturing and I4.0

With the advent of I4.0, the researchers focused on identifying the relationship between Lean Manufacturing and I4.0 and how the I4.0 technologies are incorporated into the Lean Manufacturing environment. The research can be broadly categorised into how 'Lean Manufacturing enables effective implementation of I4.0 technologies' and how 'I4.0 technologies enhance lean tools capability'. Limited studies also pointed out the barriers associated with the integration of I4.0 and Lean Manufacturing. With Lean Manufacturing's impact on I4.0, researchers have indicated that Lean Manufacturing acts as a precondition for I4.0, as once the waste is eliminated from the processes, it enables I4.0 adoption (Amjad *et al.*, 2020; Ciano *et al.,* 2021 and Fortuny-Santos, *et al.,* 2020). Bittencourt *et al.* (2021) suggested that Lean Manufacturing is an enabling effect and a trigger for implementing I4.0 technologies. Interestingly, one instance was observed where the introduction of I4.0 technology led to increased productivity. Still, the layout was not optimised, lacked standardisation, and faced several issues, such as a pile-up of work-in-progress, a mix of lots, etc. (Ciano *et al.,* 2021). Thus, Lean Manufacturing ensures the establishment of a waste-free/well-defined process for an effective I4.0 implementation. Buer *et al.* (2018) claimed that a production environment that has implemented Lean Manufacturing provides a more accessible platform for smart manufacturing implementation. Tortorella and Fettermann (2018) indicated that companies which widely implement Lean Manufacturing practices are most likely to adopt I4.0

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technologies. Pagliosa *et al.* (2019) proposed that companies that have implemented Lean Manufacturing and want to take advantage of I4.0 technologies should invest in CPS and IoT, as they found high synergy levels with Lean Manufacturing principles. Rossini *et al*. (2019) conducted an empirical study on European manufacturers and concluded that companies that aim to implement higher levels of I4.0 must have previously implemented lean production practices. Although several researchers depict a strong relationship between the two methodologies, Črešnar *et al.* (2020), through the structural equation modelling techniques of a data set of 323 responses from Slovenian organisations, concluded that Lean Manufacturing is not associated with I4.0 readiness. This can be attributed to the fact that Slovenian manufacturers do not use Lean Manufacturing compared to other tools and are more focused on the process (Črešnar *et al.*, 2020). However, they also propose the importance of Lean Manufacturing in implementing I4.0 technology.

Furthermore, not all lean principles have a strong effect on I4.0 technologies, soft lean principles such as 5-why's, Employee empowerment, Genchi Genbutsu, Ringi decision-making (traditional Japanese decision-making process), etc., have been found to have a very low impact on I4.0 technologies as these are mainly based on communication and creativity (Ciano *et al.*, 2021; Rosin *et al.*, 2020). Genchi genbutsu (i.e., the Japanese term for "Go and See") is a vital element of the Toyota culture, which allows people within Japanese factories to gain a deeper understanding of "everyday events and the root causes of problems" (Chiarini *et al.*, 2018). Ringi refers to the traditional decision-making process in Japanese companies. The word 'Ringi' consists of two parts, the first part 'Rin' means to submit a proposal to a supervisor, and the second part is 'Gi' means consultation and decision-making (Rosin *et al.*, 2020).

With 'I4.0 technologies enhancing the capability of lean tools', authors have followed two different approaches. Firstly, they propose how specific individual I4.0 technology can incarnate the Lean Manufacturing approach, such as big data to improve decision-making, continuous improvement, value addition, and waste reduction (Ghouat *et al.,* 2021 and Trstenjak and Cosic, 2019), IoT-enabled data analytics to enhance the decision support system (Abd Rahman *et al.,* 2021), Cobots for lean automation (Rossi *et al.*, 2020), Cloud Computing (CC) with ML to enhance the Kanban system and propose Cloud Kanban (Shahin *et al.,* 2020), and integrated Lean Value Stream which integrates seven I4.0 technologies (Tortorella *et al.*, 2020b).

Secondly, the authors have identified how combining different I4.0 technologies can impact each lean tool's delivery performance (Pereira *et al.*, 2019; Rosin *et al.*, 2020; Saxby *et al.*, 2020; Valamede *et al.*, 2020). Thus, researchers suggested that I4.0 technologies significantly impact various lean tools. However, the impact varies with each technology; hence, for every I4.0 technology, high impact lean tools have been identified (Raji *et al.*, 2021). Chiarini *et al.* (2020) analysed the advantage of I4.0 to enhance the lean tool's capability and concluded that Total Productive Maintenance (TPM) is the highly-rated tool to do so.

There also have been efforts to understand the barriers associated with the integration of I4.0 and Lean Manufacturing. Vigneshvaran and Vinodh (2020) proposed 16 barriers that firms can consider for successful implementation. Some important barriers are 'increasing competitive pressure', 'lack of management support', 'lack of long-term vision', and 'lack of capital fund'. Saabye *et al.* (2020) provided barriers from a learning organisation perspective that can be considered in the integration of Lean Manufacturing and I4.0 to improve production performance. Some of the barriers from a learning organisation perspective are operators not

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having second-order problem-solving abilities, problem-solving not initiated by operators, operators perceiving new technology as coercive, lack of leadership supporting learning, and poor learning processes and environments. By identifying these barriers for their organisations, managers can plan for appropriate tools and technologies to be considered in achieving enhanced performance.

3.2.2. Lean Manufacturing and I4.0 implication on performance

Researchers have also demonstrated a positive impact on enterprise performance, financial performance, and other areas of customer satisfaction, quality, workplace safety, environment, and operations.

Adopting I4.0 technologies will involve a high cost of investment, and the returns on the capital are vital, where the financial performance becomes a key factor of its acceptance. Researchers have demonstrated positive financial returns after implementing I4.0 technologies (Calabrese *et al.*, 2020; Raji *et al.*, 2021). In a case study, a manufacturing firm had invested 68% of its revenue in the first year, followed by 38.2% and 41.5% in the second and third years on its revenues in the I4.0 technologies, and has successfully achieved a return on investment (ROI) in just 3.6 years (Ghobakhloo and Fathi, 2019). Pamornmast *et al.* (2019) also claimed significant financial performance of Lean Manufacturing and I4.0 based on the interview with 302 individuals from pharmaceutical companies in Thailand. Financial benefits can be linked to flexible, modular, and customer-tailored production concepts, whereas additional revenue can come from digitalising the products and services (Dutta *et al.*, 2020). Varela *et al.* (2019) investigated the impact of Lean Manufacturing and I4.0 on the sustainability aspect and conveyed that I4.0 has a strong relationship with economic sustainability but couldn't establish a relationship between Lean Manufacturing and economic sustainability. They concluded that this does not necessarily indicate a relationship between Lean Manufacturing and economic sustainability.

Digitisation of production increases efficiency, which ultimately also improves customer satisfaction. I4.0 technology significantly impacts customer satisfaction by meeting various KPIs, such as response time to customers, delivery lead time, line reliability, etc., (Raji *et al.*, 2021). Digital technologies enable transparency in the production process, providing customers with better insight into the manufacturing of their products (Beliatis *et al.*, 2021). Digital technologies help optimise the manufacturing lead time by identifying and reducing the bottleneck in the process. Applying I4.0 in lean supply chain practices positively impacts aspects like flexibility, reduced inventory levels, faster deliveries, etc., contributing to customer satisfaction (Ciano *et al.*, 2021).

The Key Performance Indicators (KPIs) of quality are also positively impacted by I4.0 technologies; mainly, the defects detected per unit produced are most impacted by the integration (Raji *et al.*, 2021). The monitoring capabilities of the I4.0 technologies have resulted in a reduction of errors in production, such as order picking and dispatching, as well as those related to production. They have enhanced the quality of operations (Calabrese *et al.*, 2020).

Workplace safety is one of the vital aspects of any operation, and I4.0 technologies have been shown to impact the KPIs for enhancing healthy and safe working environments (Raji *et al.*, 2021). Through the application of drones and robots, the risky production task has been automated, improving workplace safety (Calabrese *et al.*, 2020).

I4.0 technologies enable the production process to shut down the machines based on the capacity requirements and save energy, also, the technology allows for the combination of

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multiple machines into a single machine which reduces the carbon footprint (Felsberger *et al.*, 2020). A smart energy system drives maximum potential from renewable resources, and smart grids and smart factories promote constant energy monitoring, thus reducing the carbon footprint (Amjad *et al.*, 2020).

In terms of operational performance, several researchers have shown a positive influence on various aspects of production, such as productivity, delivery service level, inventory level, scrap, and rework. (Buer *et al.*, 2021; Dutta *et al.*, 2020; Kamble *et al.*, 2020; Tortorella *et al.*, 2019d and Tortorella *et al.*, 2021). Abd Rahman *et al.* (2021), through their Lean Manufacturing Decision Support System (LMDSS) framework, demonstrated an improvement in the line efficiency by 18.5% and a reduction in the operator count by one and also a decrease of 3 workstations. The integration of two methodologies has also been shown to reduce the delivery time, which is evident in a case study of an additive manufacturing facility to reduce the cooling time through the ML algorithm (Agostini and Filippini, 2019). There is a benefit seen in the transport lead time reduction, inventory accuracy, and less rework and reissue requirements in the supply chain context of an organisation through a network approach where the logistics operator's efficiency is improved through real-time information on the material status (Felsberger *et al.*, 2020). After implementing the manufacturing digitalisation project, the organisation realised improvements in better teamwork and communication across the plant, less paperwork, better order fulfilment, and workflow efficiency (Ghobakhloo and Fathi, 2019). Tortorella *et al.* (2019c) stressed the importance of product/service-oriented technologies such as CC, IoT, and BDA in achieving high operational performance by enhancing decision-making. Their study also provides the right balance between adopting I4.0 technologies and Lean Manufacturing practices to improve operational performance.

3.2.3. Lean Manufacturing and I4.0 framework

Authors have proposed various frameworks with diverse interests in integrating Lean Manufacturing and I4.0 technologies. Pacchini *et al.* (2019) developed a model to measure the degree of readiness for implementing I4.0, by identifying eight enabling technologies and defining the prerequisites for each of the enabling technologies. Pozzi *et al.* (2021) proposed a model for determining the improvements that can be realised by integrating Lean Manufacturing and I4.0 technologies and distinguishing between incremental/evolutionary and radical/revolutionary improvement. Abd Rahman *et al.* (2021) developed a theoretical framework that integrates Lean Manufacturing, data analytics, and the IoT to enhance the decision support system for process improvement. Amjad *et al.* (2021) prepared a framework to synergise LARG (Lean, Agile, Resilient, and Green) manufacturing with I4.0 technologies consisting of 11 phases and 31 steps in which various I4.0 technology have supplemented the LARG paradigm. Tortorella *et al.* (2021) presented a pathway for high-performance lean automation to indicate the implementation sequence, which falls into three sets of start-up, in-transition, and advance, representing the various lean principles and I4.0 technologies in each pathway. Ciano *et al.* (2021) proposed a pairwise framework for Lean Manufacturing and I4.0 technology integration; the framework consists of six areas, including manufacturing equipment and processes, new product development, shop-floor management, supplier relationship, customer relationship, and workforce management covering the entire supply chain. Tortorella *et al.* (2020a) developed a lean automation framework describing how process-oriented, product-oriented, and service-oriented I4.0 technologies can be integrated into supplier-related, customer-related, and internally-related Lean Manufacturing practices. Xu and Chen (2018) formulated an IoT-based framework to support dynamic production planning and scheduling in the Just-In-Time environment by identifying and addressing the challenges faced in the JIT manufacturing environment.

3.2.4. Lean Manufacturing and I4.0 integration with other methodologies

As customer needs keep changing and increasing in the global competition, companies have started adopting the latest technologies and hybrid methodologies like lean and agile, lean and green, LARG, and lean six sigma (LSS) to stay competitive. This signifies that each company has a different set of challenges and competition; hence, they need to plan a unique strategy to counter them. Thus, following only Lean Manufacturing by integrating with I4.0 technology will not suffice the requirement, and integration of other methodologies is necessary.

Organisations have adopted lean and agile as a combined methodology to become flexible and respond quickly to volatile changes in customer requirements. A cross-case analysis by Raji *et al.* (2021) depicted the impact of the I4.0 technologies on lean and agile practices, with some technologies exhibiting a weak impact and most of the technologies having a moderate to high impact.

The combination of the lean and green approach is mainly to achieve high operational performance without compromising on the environmental impact. Leong *et al.* (2020) presented an enhanced adaptive model for the integration of I4.0 technologies with the lean and green approach. A Lean and Green Index (LGI) is coupled into the model, and the best-optimised strategy is determined through machine learning. The LGI target is updated automatically when a set target is achieved for continuous improvement.

Amjad *et al.* (2020) studied the integration of constituents of Lean, Agile, Resilient, and Green (LARG) manufacturing with I4.0 technologies and confirmed the benefits in terms of operational, economic, and environmental areas. In another research, Amjad *et al.* (2021) developed an implementation framework and concluded that the collaboration between the LARG manufacturing and I4.0 technologies would improve production performance.

Chiarini and Kumar (2020) demonstrated the effective integration of LSS and I4.0 technologies and proposed that LSS provides a platform to provide effective outcomes from the I4.0 technologies. They suggest the use of an e-Kanban pull system with low inventory and uninterrupted flow for horizontal integration. Vertical integration and end-to-end integration are also achieved by reengineering ERP modules such as Manufacturing Execution System (MES), Supervisory Control And Data Acquisition (SCADA), Material Requirements Planning (MRP), Customer Relationship Management (CRM), with I4.0 technologies like Cyber-Physical System (CPS), IoT, Smart Sensors etc. Yadav *et al.* (2020) studied the impact of the integration between I4.0, LSS, and Quality Management System (QMS) on 22 performance indicators and confirmed statistically significant differences in 20 performance indicators consisting of quality, sales, delivery, inventory and so forth. However, only absenteeism and throughput indicators did not significantly differ in responses.

3.2.5. Application of I4.0 technologies in Lean Manufacturing

IoT technologies such as Radio-frequency identification (RFID) and Low Power Wide Area Network (LPWAN) are used to enhance digital traceability and provide real-time information that can be effectively used in Lean Manufacturing, to identify and eliminate waste (Abed *et al.*, 2020 and Beliatis *et al.,* 2021). Through online monitoring of RFID, Chen and Chen (2014), designed an automatic generation of Value Stream Maps (VMS) using computer-aided programming. IoT has also been used to integrate machines on the shop floor and connect the machines with Andon systems to enhance the decision support system for process improvement

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(Abd Rahman *et al.*, 2021; Ito *et al.,* 2020). IoT has also been applied to transform the traditional JIT (Just-In-Time) into dynamic JIT, which successfully addresses the challenges of traditional JIT by integrating modules integrated with IoT technologies into the MES (Xu and Chen, 2018). IoT application is also shown to benefit the concept of Single Minute Exchange of Die (SMED) by providing embedded information to the product that can be directly communicated to the machine that requires a changeover, ensuring shorter changeover time through direct communication (Sanders *et al*., 2016). IoT has also shown effective synchronisation between production and logistics by providing the logistic operator with real-time requirements and showing optimum travel routes to improve process efficiency (Zhang *et al*., 2019).

Machine Learning (ML) is used to enhance the decision support system in effectively delivering a JIT delivery performance. Flexibility is provided for the operator with re-scheduling options in case of production issues using a human-machine interface (Yao *et al*., 2020). ML contributes to the continuous improvement philosophy by targeting specific performance indicators of complicated data-driven processes. This is achieved by automatically choosing the best improvement pathway under dynamic changes in production, which would otherwise have been a tedious task manually (Leong *et al*., 2020). ML also contributes to the reduction of the lead time of the process by accurately predicting the cooling time in the additive manufacturing process (Osswald *et al.*, 2020).

Cobots are used effectively in the Lean Manufacturing environment to promote automation through the careful design of grippers to meet the safety norms to effectively integrate the simultaneous operation of operator and robot (Rossi *et al.,* 2020).

Augmented reality (AR) has been used to enhance the Jidoka system, with examples of an operator using smart 3D glasses to visualise picking the right critical bolt. This, in turn, facilitates the operator in choosing the right wrench and ensuring the operator tightens with the right torque and only then will allow the next task (Chiarini and Kumar, 2020). Trakadas *et al*. (2020) also suggested AR on wearable devices that support gestures to reduce the impact on employees' operativity. This system supports the human-in-loop layer, which enables the interaction between humans and AI.

Virtual reality (VR) has been used to create a digital twin of the actual manufacturing process before the actual installation to provide the manufacturing team to confirm the design in the virtual world and rectify the problems before the actual installation (Pérez *et al*., 2020). This integration of VR in the confirmation process ensures a reduction in the rework and reduces the project's lead time by ensuring fewer problems after installation.

Artificial Intelligence (AI) uses electroencephalography sensors to characterise and discern between various types of behaviour. This practice is carried out on a balanced scorecard and hoshin kanri tree and conveys the unique characteristics observed by the process operator and the leader (Schmidt *et al*., 2020). These devices are effective in imparting the training of the lean principles on the shop floor where valuable feedback can be given by differentiating between the systems and gaining a better understanding of the thinking patterns.

Cyber-Physical System (CPS) is used to create real-time scheduling and dispatching system that runs on a dynamic VMS; it can monitor the flow of the products and spot the discrepancy between the physical and virtual world caused by lean waste (Ramadan *et al.*, 2020). CPS is also deployed by integrating with the pull production strategy to reduce the cost involved in the implementation. This is done by striking a balance between the extent of CPS implementation and the performance through an appropriate pull control strategy (Huang *et al*., 2021). CPS was used in implementing the Jidoka system to determine the optimum time

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for the tool wear in a CNC process and initiate automatic tool change by reducing the need for the operator to perform the repetitive task (Romero *et al*., 2019). Ma *et al.* (2017) also proposed a CPS-enabled smart Jidoka system to provide flexible combination and performance for the assembly of connecting rod bearing shells and main bearings in an engine assembly line. CPS application can also be seen in the application of digital torque wrenches in the assembly line, where the operator is provided with screens that indicate the torque data and also indicate with green and red lights about the completion of the job or error (Cirillo *et al.,* 2021). The system ensures poka-yoke under abnormal conditions by not allowing the tool to unlock to perform the next task.

Cloud Computing (CC) is implemented in a dashboard-type monitoring of the process, which enables managers to make effective decisions (Shahin *et al*., 2020). CC and RFID are used to grasp the real-time production records of production operators and the production equipment for a labour-intensive production company (Guo *et al*., 2015). CC is integrated with the ERP system to create a cloud ERP system that supports electronic Kanban, real-time monitoring of production volumes promoting JIT, FMEA (Failure mode effect analysis) of process, and also supports preventive maintenance, spare part management, and tracking machine breakdown history (Ghobakhloo and Fathi, 2019).

Bid Data Analytics (BDA) is effectively integrated with various guidelines of Value Stream Mapping (VMS) to enhance and benefit the VMS design. It enables real-time takt definition and effective decision-making in selecting finished goods strategy. BDA can successfully permit the re-dimensioning of supermarket policies and, along with remote production process management, would allow instant updates regarding fluctuations and variations, which can halt interval achievement (Tortorella *et al*., 2020b). BDA is also effectively used to anticipate machine breakdowns by monitoring the faults and maintenance data generated from the machines (Raji et al., 2021 Tortorella *et al*., 2021).

3.2.6. Important lessons learned

The following points summarise the most important lessons learned:

a) Lean Manufacturing acts as a precondition for I4.0, as once the waste is eliminated from the processes, it enables I4.0 adoption (Amjad *et al*., 2020; Ciano *et al.,* 2021 and Fortuny-Santos, *et al.,* 2020).
b) Companies widely implementing Lean Manufacturing practices are most likely to adapt I4.0 technologies (Tortorella and Fettermann, 2018).
c) Companies that aim to implement higher levels of I4.0 must have previously implemented lean production practices (Rossini *et al*., 2019).
d) I4.0 technologies enhance lean tools' capability.
e) Big data improves decision-making, continuous improvement, value addition, and waste reduction (Ghouat *et al.,* 2021 and Trstenjak and Cosic, 2019).
f) I4.0 enhances the lean tool's capability and concludes Total Productive Maintenance Chiarini *et al.,* 2020).
g) There will be positive financial returns after implementing I4.0 technologies (Calabrese *et al*., 2020 and Raji *et al*., 2021).
h) I4.0 and lean strongly relate to economic sustainability (Varela *et al.,* 2019).
i) I4.0 technology and Lean significantly impact customer satisfaction, meeting various KPIs such as response time to customer, delivery lead time, line reliability, etc, (Raji *et al*., 2021).

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j) From the authors' point of view and experience, I4.0 and lean will promote sustainability even more and at a faster rate in the digital era.

4. Key recommendations for future research

This paper has conducted a systematic literature review to analyse and synthesise existing literature on Lean Manufacturing - I4.0 integration. In total, 60 relevant journal articles have been identified during the review. It is clear that this is an emerging research area, in which around 68% of them were published during the last two years (i.e., 2020-2021). This section attempts to propose key recommendations for future research based on which the current body of literature does not adequately address or respond to. Future research should focus on filling these obvious gaps in the literature:

1) Managerial and organisational aspects in Lean Manufacturing and I4.0 integration
2) Impact of socio-cultural and socio-economic context for Lean Manufacturing and I4.0 integration in developed and developing economies
3) Lean Manufacturing and I4.0 key recommendations for SMEs
4) I4.0 technologies integration in an LSS environment
5) Lean implementation level on the integration with I4.0 technologies
6) I4.0 effect on Total Productive Maintenance (TPM)

4.1. Managerial and organisational aspects in Lean Manufacturing and I4.0 integration

Although the integration of Lean Manufacturing and I4.0 technologies can augment the lean principles and bring digitalisation and automation to the process, the role of humans in technological development is inseparable. The role of employees is crucial as the technology is not intelligent, and it has to be implemented properly to work well (Agostini and Filippini, 2019). However, I4.0 technology adoption will lead to a decrease in the low-skills task of employees like repetitive tasks, and it will increase the high-skills task like process control, planning, etc. (Bonekamp and Sure, 2015). In the digital era, a different set of competencies, like social competence, self-competence, professional and methodology skills, etc., are required by the workforce to work with the I4.0-enabled processes (Fortuny-Santos *et al.*, 2020). Although an employee's role is an important aspect, resources are still scarce on the subject. Existing research has failed to address specific skills at an organisational and managerial level, which plays a vital role in the success factor of I4.0 adoption. Hence, creating a framework to address this gap for adopting I4.0 practices in a Lean Manufacturing environment can be highlighted for future research.

4.2. Impact of socio-cultural and socio-economic context for Lean Manufacturing and I4.0 integration in developed and developing economies

Tortorella *et al.* (2019c) suggested that technological adoption (I4.0 technology) alone will not lead to a competitive advantage, whereas Lean Manufacturing will establish the organisational habits and mindsets required for process improvement. Hence, the socio-technical organisation changes such as practices, and behaviours from Lean Manufacturing, when combined with technological enhancement of I4.0 technologies, enable organisations to achieve a competitive advantage. Under these Lean Manufacturing and I4.0 combination scenarios, high-technology applications and human-based simplicity simultaneously provide better performance. Researchers have identified the difference in the results obtained on studying the organisations from developed and developing countries, which can be mainly linked to sociocultural factors

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(Shahin et al., 2020; Tortorella *et al.*, 2019d). Also, manufacturing methodologies and the latest technologies implementation will be influenced by the socio-economic context as the implementation strategy cannot be the same and would need to be modified to suit the relevant economic context. There are limited studies on this area; hence, a study on the integration of Lean Manufacturing and I4.0 practices on a broader economic base, with a combination of both multi-national and local companies, will give a better insight into understanding the impact of the socio-cultural and socio-economic context.

4.3. Lean Manufacturing and I4.0 key recommendations *for SMEs*

Lean Manufacturing is now a well-established methodology in many SMEs, but I4.0 being a recent technology, their application level varies among SMEs. I4.0 technologies will provide a level playing field for all, with minimum dependencies on the economies of the size or scale of operations. So, SMEs must learn to tap the potential of I4.0 technologies to stay competitive. Although many of the technologies of I4.0 can be successfully implemented in large-scale companies, it's challenging to implement the same in SMEs. Hence, SMEs must identify the technologies which can significantly impact business functions with performance benefits (Saad *et al.,* 2021). Several literature depicts the guidelines for integrating Lean Manufacturing and I4.0 but in a general industrial / manufacturing context (Ghobakhloo and Fathi, 2019; Ito *et al.,* 2020 and Valamede *et al.*, 2020). However, there is a scarcity of research specifically focusing on the integration between Lean Manufacturing and I4.0 in an SME environment. Hence, further research on creating key recommendations for effectively integrating Lean Manufacturing with I4.0 technologies for SMEs will benefit SMEs organisations.

4.4. I4.0 technologies integration in an LSS environment

To improve operation performance, various methodologies are adopted by organisations to gain a competitive advantage. LSS has gained much popularity, and most fortune 500 companies have implemented the integrated LSS methodology (Chiarini and Kumar, 2020). However, the research article on the integration of LSS and I4.0 is scarce when compared to Lean Manufacturing. Chiarini and Kumar (2020) have demonstrated how LSS tools and I4.0 tools can be integrated to create a competitive advantage. Yet a holistic framework is not in place for their effective integration. Further research can be carried out to prepare a framework for the effective integration of LSS tools and I4.0 technologies.

4.5. Lean implementation level on the integration with I4.0 technologies

Lean Manufacturing and I4.0 technologies have a positive relationship, as established in this work, although every organisation will have a different level of lean implementation. Some firms rigorously adopt lean principles throughout their organisation across all its functions. In contrast, some firms have a moderate lean implementation, sometimes limited to specific organisational functions or specific lean tools. The current studies fail to shed light on the integration between Lean Manufacturing and I4.0 technologies based on the lean implementation level in the organisation. Authors have specifically pointed out the lean tools that positively impact integrating I4.0 technologies (Saxby *et al*., 2020). Tortorella *et al.* (2021) proposed three sets of clusters between lean and I4.0 technologies; start-up, in-transition, and advanced. They suggest performance improvement in relation to the cluster. In continuation with this work, these three clusters can also be established for defining the level of Lean Manufacturing implementation in companies based on the various tools used and the extent of

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coverage within the organisation to establish the relation with the I4.0 technologies as future research.

4.6. I4.0 effect on Total Productive Maintenance (TPM)

The integration of I4.0 technologies in Lean Manufacturing will enhance the operational efficiency of the plant and brings higher automation in the production lines. The increases in automation levels lead to the requirement for higher production efficiency. The production efficiency in an automated production line highly depends on the performance of equipment or equipment efficiency. This in turn, drives the focus on the plant maintenance department in effectively carrying out the preventive maintenance activities. To deliver higher equipment efficiency, the maintenance team should change its approach from preventative to predictive maintenance (Ghobakhloo and Fathi, 2019). Preventative maintenance is responding to the equipment problems after they have surfaced in production, whereas predictive maintenance is identifying the problems in the equipment before they create a machine breakdown and taking corrective actions to prevent such breakdowns. In this scenario, it will be interesting to note how the I4.0 technologies will contribute to achieving higher equipment efficiency by integrating with the TPM of the plant. Through I4.0 technologies, it will be possible to monitor the equipment parameters on a real-time basis and identify patterns that indicate potential equipment problems for which corrective actions can be planned effectively. TPM was also rated as one of the highly-rated tools enhanced by the I4.0 technology (Chiarini *et al.*, 2020; Raji *et al*., 2021). Further research should investigate how I4.0 technologies can enhance TPM in achieving higher equipment efficiency through empirical studies with applied case studies.
Furthermore, it has been noticed that Industry 4.0, in particular, the usage of machine learning; which is a field of artificial intelligence; can help in the case of process disruption and the transformation of predictive maintenance to prescriptive maintenance, which assists in identifying the set of integrated maintenance and production decisions that improve the effectiveness of process systems in terms of equipment failure prediction, maintenance, and production schedule (Gordon and Pistikopoulos, 2021).

5. Conclusion, contribution to knowledge and gaps, commercial impact and limitations

In the current competitive world, manufacturing companies face diverse competition characterised by changing customer expectations, intense competition, globalisation, financial crisis, and economic downturn. Under these challenging environments, for companies to be competitive, they must constantly adapt to the latest technologies and processes to maintain the sustainability of the process. I4.0 is the latest advancement in the industrial process which has been presented as a solution to ensure the productive sector's success in the digital area but must be aligned with organisational process improvement to guarantee such sustainability. Hence, different aspects of Lean Manufacturing and I4.0 integration have been explored in this paper as a potential approach to achieving such alignment. However, development in this area is still in its infancy, and most articles in this area have been published in the last two years.

5.1. Contribution to the body of knowledge and identifying research gaps

As one of the few systematic literature reviews in this field, this research work contributed to the systematic review of the existing state of knowledge in the integration of Lean Manufacturing and I4.0 and proposed a thematic map to organise, categorise, and structure the current studies. Five main research themes were identified in the area of Lean Manufacturing and I4.0 (see figure 7 and sections 3.2.1 to 3.2.5). From the findings, various gaps in the

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literature were identified that can be considered as key recommendations for future research on this topic (see sections 4.1 to 4.6).

5.2. Commercial impact

Lean principles will contribute to the commercial side of any organisation by reducing the type of waste, shortening the timeline between customer orders and shipment, high quality and reliability and the application of total productive maintenance and avoiding sudden reduction in the capacity of the resource. This research paper identified that Lean and I4.0 are highly complementary, and the synchronisation of the vast data generated at different stages in the supply chain through the different I4.0 digital technologies will contribute positively to the principles of lean and make great sense to the need for the integration of both lean and I4.0, which will significantly influence organisations' business and strategy and help to expand their market due to the digital technologies and have broader economies of scope which is one of the lean's emphasis.

5.3. Impact on society and education

Clearly, society doesn't acquire the required skills to cope with the application of digital technologies in lean organisations. There is a two-dimensional problem in this regard: neither the lean practitioners are fully aware of the digital technologies and data analytics, nor the digital professionals are entirely knowledgeable about the lean principles. This proves the need to update lean practitioners and digital professionals on Lean and I4.0. Universities should also provide specialised courses to cover Lean and I4.0 and their integration; the research team of this paper have already started this mission within the community.

5.4. Limitations

As the research was carried out based on the integration of Lean Manufacturing and I4.0 technologies in a manufacturing environment, there is a possibility of a restriction in the technologies, or the practices based on the specified context. In the SLR approach, three scholarly databases were considered for the research and there may be a possibility of overlooking or missing a few studies due to the researchers' choice of search string and database for publication. In addition, where the articles not published in English were not considered, they might have relevant findings. Furthermore, a small number of articles in the context of Lean Manufacturing and I4.0 technologies is insufficient to arrive at a generic conclusion.

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`List of Tables:

Table I. Industry 4.0 technologies and description

Industry 4.0 technology	Description
Internet of Things (IoT)	IoT is the internet networking that integrates humans with machines or devices, to gain real-time output which can be used for achieving superior quality, flexibility, cost reduction, and lead time reduction (De Vass *et al.,* 2018).
Machine Learning (ML)	ML is a type of computer program, which is capable of learning from experience to improve a performance measure for a given task (Usuga Cadavid *et al.,* 2020).
Collaborative Robots (Cobots)	Cobots is an approach that allows the direct physical interaction between robots and humans without the need for physical safeguarding, under specific conditions (Magrini *et al.,* 2020).
Augmented reality (AR)	AR is a set of communication systems, which enables humans to interact with smart technologies like 3D glasses, screens, exoskeletons, etc. that can augment human abilities (Chiarini and Kumar, 2020).
Virtual Reality (VR)	VR is a means of simulating reality. It is famously used for entertainment purposes, but lately, we can see a lot of applications in manufacturing industries with safe human-machine interaction (Pérez *et al.,* 2019).
Artificial Intelligence (AI)	AI corresponds to the tasks carried out by machines, which are normally carried out by human intelligence (Chiarini and Kumar, 2020).
Cyber-Physical System (CPS)	For producing highly customised and low volume batches, the CPS-based technology allows the production system to be changeable and modular and ensures that the production system is profitable (Huang *et al*., 2021).
Cloud Computing (CC)	CC provides integrated communication between the highest level (hierarchy) of the organisation and the technology level (CPS and smart products). It enables data sharing across the enterprise, provides agility and flexibility, and improves the performance of the system with lower costs (Valamede *et al.*, 2020).
Big Data Analytics (BDA)	BDA is characterised by big volume, variety, and velocity of data across a wide range of networks, whereas analytics is the decision support system which enables the firm in analysing the data for evidence-based decision making and taking action (Wang *et al*., 2018).

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Table II. Detail of the research team

Academics involved in the research	Expertise related to this research	Role and responsibility toward this research
A professor	Over 20 years of industrial experience in lean and six sigma implementations at multi-national engineering companies in the UK, integrated manufacturing and measuring enterprises' Industry 4.0 readiness. Also, the developer of lean and six sigma and digital manufacturing systems modules for the postgraduate courses.	Hold and attend the milestone research team meetings to discuss ideas, plan, inclusion and exclusion criteria, analysis, synthesis and screening.
A principle Lecturer	More than ten years of experience in automation and I4.0 implementation.	Hold and attend the milestone research team meetings to discuss ideas, plan, inclusion and exclusion criteria, analysis, synthesis and screening.
A Senior Lecturer	More than ten years of experience in digital supply chain and lean and six sigma applications in the digital era. Involved in the teaching of related modules at postgraduate levels.	Hold and attend research team meetings to discuss ideas, plan, inclusion and exclusion criteria, analysis, synthesis and screening. Monitoring the progress of the research.
A Research Student	Interested in industrial management with a strong background in automobile manufacturing and lean implementation.	Attend all meetings and execute the daily research activities based on the academics' advice.

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Table III. Database and Search Strings

Database	Search String
Web of Science	TS = (lean OR " Just In Time " OR JIT) AND TS = (manufacturing) AND TS = ("Industry 4.0" OR "Industry revolution IR 4.0" OR "Industry revolution 4.0" OR "smart factory" OR "smart manufacturing")
Scopus	TITLE-ABS-KEY (lean OR {Just In Time} OR JIT) AND TITLE-ABS-KEY (Manufacturing) AND TITLE-ABS-KEY ({Industry 4.0} OR {Industry revolution I 4.0} OR {Industry revolution 4.0} OR {smart factory} OR {smart manufacturing})
ProQuest	(lean OR " Just In Time " OR JIT) AND (manufacturing) AND ("Industry 4.0" OR "Industry revolution I 4.0" OR "Industry revolution 4.0" OR "smart factory" OR "smart manufacturing")

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Table IV. Classification of articles used in the literature survey under the Lean Manufacturing-I4.0 integration topic

Research Methodology	Articles
Case Study	Raji *et al.* (2021); Beliatis *et al.* (2021); Pozzi *et al.* (2021); Leong *et al.* (2020); Yao, *et al.* (2020); Osswald *et al.* (2020); Ciano *et al.* (2021); Felsberger *et al.* (2020); Rossi *et al.* (2020); Abed *et al.* (2020); Pérez *et al.* (2020); Schmidt *et al.* (2020); Shahin *et al.* (2020); Ramadan *et al.* (2020); Ghobakhloo and Fathi (2019); Ito *et al.* (2020); Xu and Chen (2018); Huang *et al.* (2021); Saabye *et al.* (2020); Zhang et al. (2019); Guo *et al.* (2015); Chen and Chen (2014); Ma *et al.* (2017).
Conceptual Study	Ghouat *et al.* (2021); Abd Rahman *et al.* (2021); Trakadas *et al.* (2020); Valamede *et al.* (2020)
LR	Amjad *et al.* (2021); Amjad *et al.* (2020); Calabrese *et al.* (2020); Fortuny-Santos *et al.* (2020); Rosin *et al.* (2020); Pereira *et al.* (2019); Buer *et al.* (2018); Sanders *et al.* (2016); Bittencourt *et al.* (2021); Pagliosa *et al.* (2021); Romero *et al.* (2019); Trstenjak and Cosic (2019).
Survey	Tortorella *et al.* (2021); Buer *et al.* (2021); Chiarini and Kumar (2020); Črešnar *et al.* (2020); Tortorella *et al.* (2020a); Tortorella *et al.* (2020b); Dutta *et al.* (2020); Chiarini *et al.* (2020); Tortorella *et al.* (2019c); Tortorella *et al.* (2019d); Kamble *et al.* (2020); Varela *et al.* (2019); Agostini and Filippini (2019); Tortorella and Fettermann (2018); Cirillo *et al.* (2021); Yadav *et al.* (2020); Vigneshvaran and Vinodh (2020); Rossini *et al.* (2019).
Mixed Methods	Saxby *et al.* (2020); Pacchini *et al.* (2019); Pamornmast *et al.* (2019)

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