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The Evolution and Future of Lean Six Sigma 4.0

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The Evolution and Future of Lean Six Sigma 4.0

Abstract

Purpose: This purpose of this study is to provide an overview of the current state of research on Lean Six Sigma (LSS) and Industry 4.0 and the key aspects of the relationships between them. The research analyses Lean Six Sigma's evolution and discuss the future role of Lean Six Sigma 4.0 in an increasing digitalised world. We present the benefits and motivations of integrating Lean Six Sigma and Industry 4.0 as well as the critical success factors, and challenges within this emerging area of research.

Design/methodology/approach – A systematic literature review methodology was established to identify, select, and evaluate published research.

Findings: There is a synergistic nature between Lean Six Sigma (LSS) and Industry 4.0. Companies having a strong LSS culture can ease the transition to Industry 4.0 while Industry 4.0 technologies can provide superior performance for companies who are using LSS methodology.

Practical Implications– This study reviews the evolution of Lean Six Sigma and its integration with Industry 4.0. Organisations can use this study to understand the benefits and motivating factors for integrating Lean Six Sigma and Industry 4.0, the Critical Success Factors, and challenges to such integration.

Research limitations – One limitation of this research was that as this area is a nascent area, the researchers were limited in their literature review and research. A more comprehensive longitudinal study would yield more data. There is an opportunity for further study and analysis.

Originality/value – This is the first systematic literature review on Lean Six Sigma 4.0 and can provide insight for practitioners, organisations, and future research directions.

Keywords: Lean Six Sigma, Industry 4.0, Continuous Improvement, Lean and Green

Paper Type: Systematic Literature Review

1. Introduction

With the arrival of the first Industrial Revolution, manufacturing evolved into mass production from being a craft or cottage industry and into Lean manufacturing with Leaner supply chains. Lean as an operational excellence methodology and philosophy that aspires towards the systematic elimination of waste through the continuous development of people (Womack, and Jones, 1996), (McDermott *et al.*, 2022) . In recent years Lean Six Sigma (LSS) has been put forward as an integration of Lean and Six Sigma. As put forward by George in 2002, the integration has the advantage of combining the reduction of waste via Lean practices and the reduction of variation via Six Sigma (George, 2002). This integration of Lean and Six Sigma as LSS can be seen as the first evolution of LSS and we refer to this as LSS 1.0.

Organisations have traditionally deployed LSS to aid competitiveness and profitability as well as increased efficiencies. However, with the recent focus on the environmental impact of organisations and environmental awareness, organisations try to deploy and achieve green objectives by utilising LSS methods (Cherrafi *et al.*, 2016, 2017) (Garza-Reyes, 2015). Since 2002, LSS has integrated "Green" to evolve into LSS 2.0. However, the LSS 2.0 "Green" evolution did not take off in practice until post-2001 (Yang, Hong and Modi, 2011; Garza-Reyes *et al.*, 2014; Garza-Reyes, 2015). LSS 2.0 aims to improve environmental sustainability and sustainable performance (Powell *et al.*, 2017).

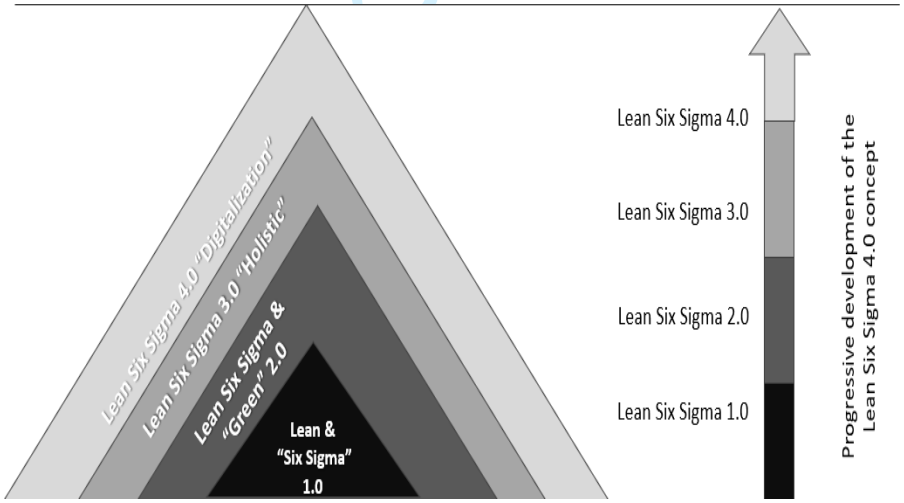

Figure 1: Evolution of LSS 4.0 "sand cone" (Antony *et al.*, 2021)

The "holistic" approach of LSS was originally put forward by Snee and Hoerl in 2002 (Snee and Hoerl, 2002; Hoerl and Snee, 2010; Snee, 2010). They put forward the holistic approach as a new 2nd evolution of LSS in "Leading Holistic Improvement with LSS 2.0" in 2018 (Snee and Hoerl, 2018). As suggested by Antony et al., (2021), the holistic approach come after the LSS integration with Green and referred to as LSS 2.0. The authors therefore suggest that the LSS holistic approach is LSS 3.0. LSS 3.0 defined as "that of an improvement system that can create, sustain and integrated improvements successfully in any environment, culture and business" (Snee and Hoerl, 2018). Moreover the holistic approach allows for the integration of a wide suite of methodologies in order to select and tailor the most appropriate tools and methodologies that can be adapted to solve problems and create and maintain improvements (Snee, 2010).

Furthermore, as manufacturing is evolving into a more digitalised environment with the evolution of Industry 4.0 (I4.0) technologies, Lean (and indeed LSS) has become more

technologically enabled (Calabrese *et al.*, 2020). Thus, the advance of new I4.0 technologies such as the Internet of Things (IoT), big data and data analytics, and augmented and virtual reality has the potential of presenting us with the fourth revolution of LSS, or LSS 4.0 (Antony *et al.*, 2021) which could potentially lead to manufacturing and service excellence (Chiarini, 2020; Chiarini, Belvedere and Grando, 2020). Another point to consider is the paradigmatic shift of organizations after implementation of I 4.0 towards circular economy(Rajput and Singh, 2019). Organizations are using digital technologies in closed loop supply chains to focuses on the restorative and regenerative aspects to enable the industrial system to adapt the concept of 'end-of-life'(Heyes *et al.*, 2018), (Jabbour *et al.*, 2018). Furthermore, these digital technologies help with restoration, elimination of the use of toxic materials, reuse and elimination of the wastage through the explicit implementation of the design models, product systems and design of the materials(Rajput and Singh, 2019). Therefore, in this phase LSS is digitally enabled to meet the needs of circular economy of the organization by enhancing the resource efficiency and environmental performance at different levels of the supply chain.

Antony *et al.* (2021) put forward a sand cone model (Ferdows and De Meyer, 1990) of Lean Six Sigma evolution (Figure 1) to demonstrate the cumulative evolution of LSS methodology from LSS 1.0 to LSS 4.0. However, the integration of LSS and I4.0 has not been empirically investigated (Kamble, Gunasekaran and Dhone, 2020; Tortorella et al., 2020), so there is uncertainty about how I4.0 and LSS can support each other. Therefore, this paper aims to investigate the following research questions:

1. *What are the motivations and benefits of integrating LSS and I4.0?*
2. *What are the critical success factors (CSF's) and challenges of integrating LSS and I4.0?*

In doing, so we believe to further the knowledge on I 4.0 and LSS, which will help organizations while implementing LSS 4.0. These questions are addressed through an evidenced based investigation. This study uses systematic literature review (SLR) methodology suggested by Tranfield, Denyer and Smart (2003), because it is indented to identify key scientific contributions in the field of LSS and I 4.0. Besides SLR methodology will help reduce bias, reduce chance effects, improve legitimacy and authority to collate evidence to draw reliable conclusions (Becheikh, Landry and Amara, 2006). The article is organized as follows: First we present the methodology adopted for SLR, subsequently descriptive analysis, followed by thematic analysis and Future research direction and at last conclusion and limitations of the study is explicated.

2. Methodology – Systematic Literature Review

This research is focused on analysing the existing literature in Operations, Operational Excellence, Quality Management and Lean Six Sigma to derive the implications of Industry 4.0 on Lean Six Sigma approaches. Various journals have published articles on the different aspects and applications of Industry 4.0 and Lean, Six Sigma and LSS. While much research has been conducted on Industry 4.0 and elements of LSS, to date, there are few studies on assessing how they can be integrated (Tortorella, Giglio and van Dun, 2019; Kamble, Gunasekaran and Dhone, 2020). The relationship of Lean and Six Sigma or LSS with digital transformation or Industry 4.0 is a gap in the literature this research aims to fill. A systematic literature review (SLR) was utilised in this study to not only understand the current status of the topic but also the fundamental gaps which can be identified through the review of literature and address them via future research studies.

Burgess, Singh and Koroglu (2006) defined a systematic literature review as studying selected articles searched from different databases and sources. Several systematic review papers have been published both in the Lean Six Sigma and quality management areas focusing on various important topics (Garza-Reyes, 2015), (Antony *et al.*, 2018), (Alcaide-Munoz and Gutierrez-Gutierrez, 2017).

Systematic reviews differ from traditional narrative reviews by adopting a replicable, scientific and transparent process that minimises bias through exhaustive literature searches of published and unpublished studies and provides an audit trail of the reviewer's decisions procedures and conclusions (Cook, Mulrow, and Haynes, 1997). An SLR differs from traditional literature review or narrative reviews (Tranfield, Denyer and Smart, 2003) on many fronts. The systematic process of searching the literature , and the subsequent extraction and synthesis is prioritised in SLRs more so compared to other literature review forms, resulting in more scientific and replicable work (Tranfield et al., 2003; Yang, Khoo-Lattimore and Arcodia, 2017).

2.1 Identification

Since I4.0 first appeared in 2011, the researcher systematically searched for articles relating to the subject matter published between 2011 and up to and including 2021, using two major academic databases such as Web of Science and Scopus. As per the approach of Tranfield, Denyer and Smart (2003), the researchers sought to create a current knowledge of the available research by synthesising the relevant body of literature. The emphasis on the systematic process of literature search, extraction and synthesis is higher in SLRs than in other forms of review, making the work more scientific and replicable (Tranfield, Denyer and Smart, 2003; Yang, Khoo-Lattimore and Arcodia, 2017; Antony et al. 2019). The search strings were applied to search all the databases mentioned above: "Lean" AND "I4.0," "Six Sigma" AND "I4.0" and "LSS" AND "I4.0". Figure 2 summarises the SLR method with a summary of the inclusion/exclusion criteria. Each researcher checked the citations and bibliographies of the selected studies to identify any additional relevant studies that were missed in the database search. Finally, grey literature (conference papers, magazine-related articles, workshops, books, editorials, prefaces, white papers) were excluded. As flowcharts are a critical part of SLR's that can ensure and improve review transparency (Petticrew, 2001; Yang, Khoo-Lattimore and Arcodia, 2017), a flowchart was utilised to draw out and map the steps within the SLP process (Figure 2). Furthermore, adopting a systematic flowchart enables future researchers to follow, replicate and draw implications from the research findings.

2.2 Screening

Initially the search identified 2,365 articles after which duplicate articles were then removed. Subsequently a review was caried out of the remaining articles and the article was retained if upon review of the article was deemed to be related to *Lean, Six Sigma and LSS and their its application within an I4.0 environment and context.* Reviews and independent assessment of the articles were carried out by the authors to assess the inclusion eligibility of the retrieved studies based on the search criteria (Parameswaran, Ozawa-Kirk and Latendresse, 2020).

2.3 Inclusion & Exclusion

Inclusion was decided and agreed by discussions and gaining consensus among the researchers. Each author read the articles independently, the full text of the articles to decide whether it fits the core research focus on LSS and I 4.0. Studies published in non-peer-reviewed journals or that were not contained in the 3 or 4 category in the ABS journal ranking (Academic Journal Guide, 2018) were also excluded. At this stage of the review, 363 studies for final inclusion were yielded. The authors made independent inclusion and exclusion lists. Wherever, there were disagreement, through a popular video conferencing software, they discussed in depth their

views on why each of the article should be included or excluded. A group level consensus was reached on the final list. This was done to ensure minimization of reviewer bias and maintaining high level of uniformity(Voola *et al.*, 2022). Management of the collation of data was via the utilisation of Zotero to save relevant citations and through Excel to record information concerning the articles under review and selected.

2.4 Synthesis & Validation

An independent review of each paper was carried out by the authors and coding was caried out utilising a meta-framework. After extraction of the final articles and recording these in Excel coding was utilised to minimise errors. Based on the sub-themes under investigation in relation to the research questions, further analysis was conducted. This analysis included the year of publication, countries of origin, authors, journals, research methods, benefits of LSS & I4 integration, motivations for LSS & I4 integration, challenges of LSS & I4 integration, and finally the CSFs for LSS & I4 integration. Utilising the SLR methodology, twenty-six articles have met all the criteria chosen for the study and they were chosen for further exploratory analysis of the sub themes of LSS & I4 integration. Both descriptive and Thematic analysis was carried out.

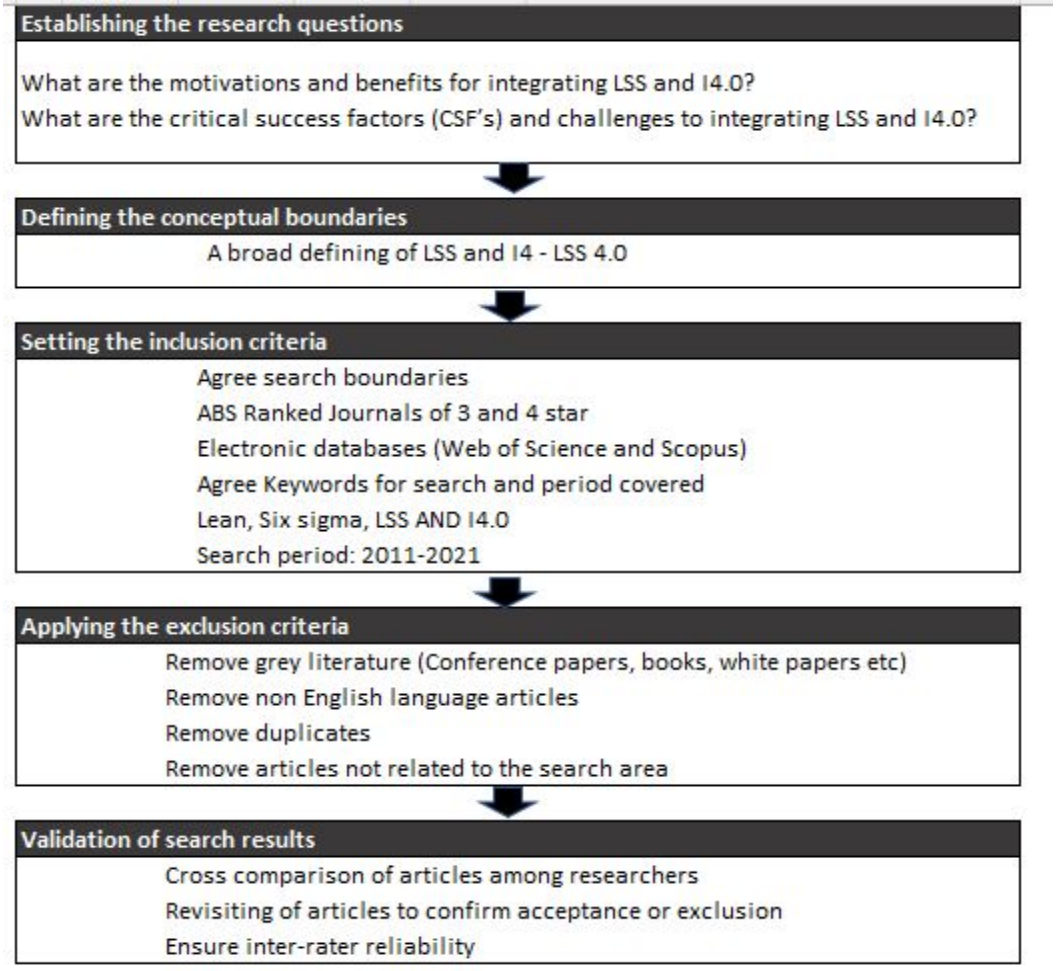

Figure 2: A summary of the SLR process

3. Descriptive Analysis

The final selected journal articles were analysed by journal type and years of publication (Figure 3). The final screened selection of twenty-six articles came from four journals. As stated previously, LSS 4.0 is still a relatively under researched area (Núñez-Merino *et al.*, 2020; Antony *et al.*, 2021). The four main journals that have been published in the area are Production Planning

& Control (48%), the International Journal of Production Research (41%), the International Journal of Operations & Production Management (7%) and the International Journal of Productivity & Performance Management (4%). This trend suggest that leading journals have already identified the potential for integration of LSS and I 4.0 and encouraging the publication of this emerging field.

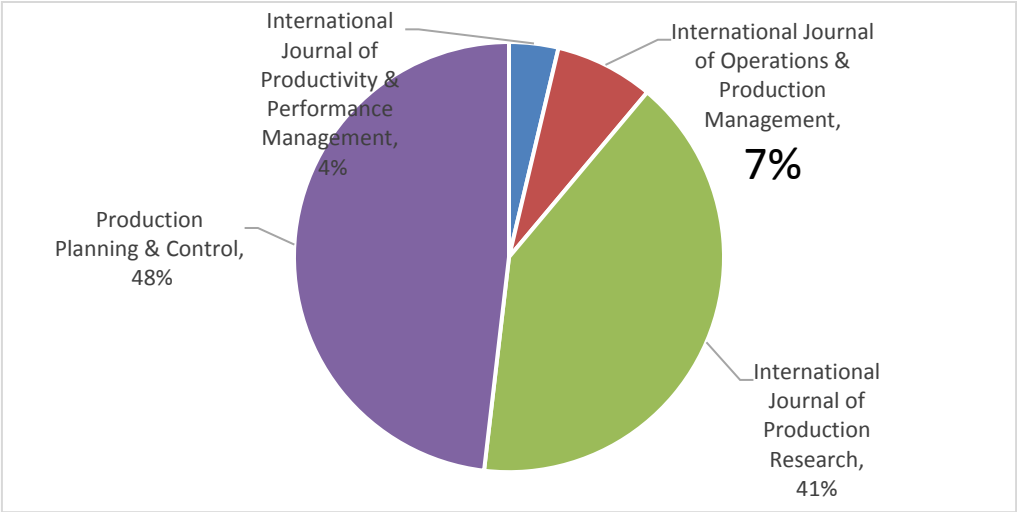

Figure 3: Categorization of articles by journals

Research related to the integration of Lean, Six Sigma, LSS and Industry 4.0 is still in the nascent stage thus has only started to appear in the literature since 2017 (Figure 4). However, there has been a gradual evolution of research into the topic commencing in 2017 and slowly increasing each year until 2021. It should be noted that most research with the exception of few articles referred to Lean integration with I 4.0 and not LSS integration with 4.0.

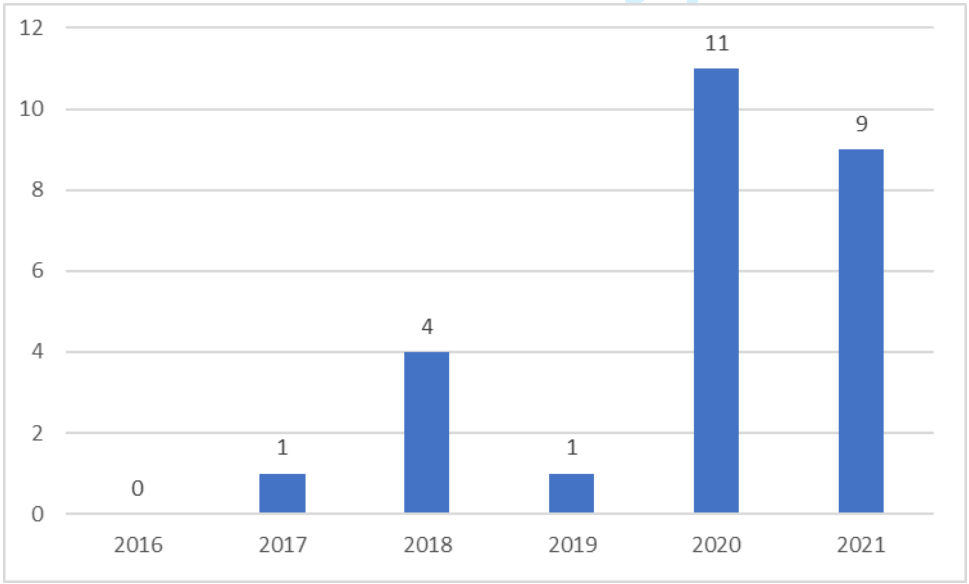

Figure 4: Categorisation of number of articles according to the year of publication

The main authors who have researched and written about the theme of Lean Six Sigma and Industry 4.0 are Tortorella (6 articles) and Kamble, Gunasekaran, Buer, Stranghagen, Giglio Chiarini and Kumar (all have published two articles each). The final selection of articles from the

SLR review was summarised in Table 1 by author, titles, year of publication and journal of publication.

Table 1: Authors, Titles, and journal names of shortlisted articles

Year	Authors	Titles	Journal
2021	Marcucci, Antomarioni, Ciarapica & Bevilacqua {Citation}	The impact of Operations and IT-related Industry 4.0 key technologies on organizational resilience	Production Planning & Control
2021	Pozzi, Rossi & Secchi	Industry 4.0 technologies: critical success factors for implementation and improvements in manufacturing companies	Production Planning & Control
2021	Ding, Ferras , Xavier; Agell	Combining lean and agile manufacturing competitive advantages through Industry 4.0 technologies: an integrative approach	Production Planning & Control
2021	Vlachos, Pascazzi, Martinez; Zobolas, Repoussis, Giannakis,	Lean manufacturing systems in the area of Industry 4.0: a lean automation plan of AGVs/IoT integration	Production Planning & Control
2021	Reyes, Mula, Diaz-Madronero,	Development of a conceptual model for lean supply chain planning in industry 4.0: multidimensional analysis for operations management	Production Planning & Control
2021	Ilangakoon, Weerabahu, Samaranayake, Wickramarachchi,	Adoption of Industry 4.0 and lean concepts in hospitals for healthcare operational performance improvement	International Journal of Productivity & Performance Management
2021	Khanzode, Sarma, Goswami,	Modelling interactions of select enablers of Lean Six-Sigma considering sustainability implications: an integrated circular economy and Industry 4.0 perspective	Production Planning & Control
2021	Tortorella, Saurin, Gaiardelli, Jurburg,	Relationships between competences and lean automation practices: an exploratory study	Production Planning & Control
2021	Pozzi, Rossi, Secchi,	Industry 4.0 technologies: critical success factors for implementation and improvements in manufacturing companies	Production Planning & Control
2020	Buer, Semini, Strandhagen & Fabio Sgarbossa	The complementary effect of lean manufacturing and digitalisation on operational performance	International Journal Of Production Research
2020	Ciano, Dallasega, Orzes & Rossi	One-to-one relationships between Industry 4.0 technologies and Lean Production techniques: a multiple case study	International Journal Of Production Research
2020	Chiarini, Belvedere & Grando	Industry 4.0 strategies and technological developments. An exploratory research from Italian manufacturing companies	Production Planning & Control
2020	Chiarini & Kumar	Lean Six Sigma and Industry 4.0 integration for Operational Excellence: evidence from Italian manufacturing companies	Production Planning & Control
2020	Kamble, Gunasekaran & Dhone	Industry 4.0 and lean manufacturing practices for sustainable organisational performance in Indian manufacturing companies	International Journal Of Production Research
2020	Núñez-Merino, Maqueira-Marín, Moyano-Fuentes & Martínez-Jurado	Information and digital technologies of Industry 4.0 and Lean supply chain management: a systematic literature review	International Journal Of Production Research
2020	Rosin, Forget, Lamouri & Pellerin	Impacts of Industry 4.0 technologies on Lean principles	International Journal of Production Research

Table 1: Authors, Titles, and journal names of shortlisted articles

Year	Authors	Titles	Journal
2020	Spenhoff, Wortmann & Semini	EPEC 4.0: an Industry 4.0-supported lean production control concept for the semi-process industry	Production Planning & Control
2020	Tortorella, Pradhan, Macias de Anda, Martinez, Sawhney & Kumar	Designing lean value streams in the fourth industrial revolution era: proposition of technology-integrated guidelines	International Journal Of Production Research
2020	Felsberger, Qaiser, Choudhary & Reiner	The impact of Industry 4.0 on the reconciliation of dynamic capabilities: evidence from the European manufacturing industries	Production Planning & Control
2019	Hughes, Dwivedi, Rana, Williams & Raghavan	Perspectives on the future of manufacturing within the Industry 4.0 era	Production Planning & Control
2019	Tortorella, Giglio, and van Dun	Industry 4.0 adoption as a moderator of the impact of lean production practices on operational performance improvement	International Journal Of Operations & Production Management
2018	Buer, Strandhagen & Chan	The link between industry 4.0 and lean manufacturing: Mapping current research and establishing a research agenda	International Journal of Production Research
2018	Lea Hannola, Alexander Richter, Shahper Richter & Alexander Stocker	Empowering production workers with digitally facilitated knowledge processes–a conceptual framework	International Journal Of Production Research
2018	Tortorella & Fettermann	Implementation of Industry 4.0 and lean production in Brazilian manufacturing companies	International Journal Of Production Research
2018	Yong Yin, Stecke & Li	The evolution of production systems from Industry 2.0 through Industry 4.0	International Journal Of Production Research
2017	Moeuf, Pellerin, Lamouri, Tamayo-Giraldo & Barbaray	The industrial management of SMEs in the era of Industry 4.0	International Journal of Production Research

All of the selected articles after screening were collated and categorised based on subthemes related to the research questions. This categorisation grouped the articles under the benefits of integration of LSS and I4.0, and the motivating factors for the integration of LSS and I4.0. The challenges to the integration of LSS and I4.0 and the CSF's for their integration was also reviewed (Table 2). There was a consensus across the authors of the articles selected in advocating the benefits of integrating Lean and I4.0.

Table 2: Themes emerging around LSS 4.0 after SLR of the final selection of articles

Cited article	Benefits of integrating LSS & I4.0	Motivations for integrating LSS & I4.0	Challenges of integrating LSS & I4.0	Critical Success Factors for integrating LSS & I4.0
Buer, Semini, Strandhagen & Sgarbossa (2021)	X	X	X	X
Buer, Strandhagen & Chan (2018)	X	X	X	X
Ciano, Dallasega, Orzes & Rossi (2021)	X			
Chiarini, Belvedere & Grando (2020)	X	X		

Chiarini & Kumar (2020)	X	X		X
Felsberger, Qaiser, Choudhary & Reiner (2020)	X	X		
Hughes, Dwivedi, Rana, Williams & Raghavan (2020)	X		X	
Hannola, Richter, Richter & Stocker (2018)	X	X		
Kamble, Gunasekaran & Dhone (2020)	X	X	X	X
Marcucci, Antomarioni, Ciarapica & Bevilacqua (2021)	X			
Pozzi, Rossi & Secchi (2021)	X			
Moeuf, Pellerin, Lamouri, Tamayo-Giraldo & Barbaray (2017)	X	X		
Núñez-Merino, Maqueira-Marín, Moyano-Fuentes & Martínez-Jurado (2020)	X	X	x	X
Rosin, Forget, Lamouri & Pellerin (2020)	X	X	X	X
Spenhoff, Wortmann & Semini (2021)	X			
Tortorella, Pradhan, Macias de Anda, Martinez, Sawhney & Kumar (2020)	X	X	X	
Tortorella & Fettermann (2018)	X			
Tortorella, Giglio, and van Dun (2019)	X	X	X	X
Yong Yin, Stecke & Li (2018)	X	X		
Ding, Ferras , Xavier, Agell (2021)	X	X		
Vlachos, Pascazzi, Martinez; Zobolas, Repoussis, Giannakis (2021)	X	X	X	
Reyes, Mula, Diaz-Madronero, (2021)	X		X	X
Ilangakoon, Weerabahu, Samaranayake, Wickramarachchi, (2021)	X	X		
Khanzode, Sarma, Goswami, (2021)	X	X		X
Tortorella, Saurin, Gaiardelli, Jurburg (2021)	X			X
Pozzi, Rossi, Secchi (2021)	X			

4.Thematic Analysis

Within the literature reviewed as part of the SLR, there is a recurring theme justifying the integration of LSS and I4.0. There are strong benefits and motivators for the integration. However, several challenges and CSF's to integrating LSS and I4.0 were also identified.

4.1 Benefits for Integrating LSS and I4.0

Both I4.0 and Lean aim to increase productivity and flexibility. According to Buer et al. (2021), real-time capability, decentralisation, and interoperability are the aspects of the I4.0 vision that will offer the most support to Lean manufacturing. I4.0 implementation in manufacturing organisations will transform the Lean manufacturing system into a Lean virtual manufacturing network that will connect all the manufacturers and suppliers in a single network, enabling the sharing of tangible (machines, equipment, human, etc.) and intangible assets (data, knowledge, and information) between the connected parties (Kamble et al., 2020). Thus I4.0 will enable a Leaner environment.

Lean involves socio-cultural changes that are fostered via daily simple work-floor experimentations (Baudin, 2007; Dora, Kumar and Gellynck, 2016) which may go against the expensive investments and technological expertise required by I4.0. Integration of Industry 4.0 with Lean manufacturing mainly enhances cost-competitiveness in the performance dimension and combined with agile manufacturing, and it mainly enhances flexibility (Ding, Hernandez and Jane, 2021).

I4.0 technology can enable and aid the strong integration of Just-in-time and Jidoka (Rosin et al., 2020), (Yin, Stecke and Li, 2018) which are the two major pillars of Toyota Production System (TPS). Real-time integration of I4.0 and LSS should have the advantage of generating minimal waste which is a huge advantage (Tortorella, Giglio and van Dun, 2019). Buer et al. (2021) stated that several Lean concepts can be improved by integrating I4.0 technologies. These included total productive maintenance (TPM), Kanban, production smoothing, autonomation (or Jidoka), waste elimination, and Kanban and Andon (Kamble, Gunasekaran and Dhone, 2020). In terms of I4.0 aligning of the Toyota production system, flow line, job shop, cell, flexible manufacturing system, and seru –can be integrated in to I4,.0 and applied to several production system types to help with forecasting and demand management over time (Chiarini, 2020). Data generated from I4.0 will enable Lean and aid in measuring and subsequently improving key performance indicators (KPI's) of many production systems in organisations (Hughes *et al.*, 2020). It should be mentioned that there was no article on Six Sigma /LSS and I 4.0 integration explicating about its benefits. However, LSS was integrated with Big data. They suggested the benefits would be in terms of big data analysis techniques will be beneficial for all phases DMAIC process(Gupta, Modgil and Gunasekaran, 2020). Another study Green Lean Six Sigma was integrated Big data analysis and it was found that there was real-time quality control, event-based inspection, and predictive maintenance.(Belhadi *et al.*, 2021) In a global study on 307 Six Sigma experts Antony et al (2020), explicates that integration of Six Sigma with Big Data can generate superior results for many organizations(Antony, Sony and Gutierrez, 2020). Big data is one aspect of I 4.0 and there are many facets of I 4.0 which are not studied with respect to LSS. On the basis on existing evidence, we summarise of benefits is tabulated in Table 3.

Table 3: Summary of LSS 4.0 integration benefits
I4.0 will enable a Leaner environment.
Integration of I 4.0 with Lean manufacturing enhances cost-competitiveness.
Integration of I 4.0 with Lean manufacturing especially agile manufacturing to enhances flexibility.
I4.0 technology can enable and aid the strong integration of Just-in-time and Jidoka.
Integration of I4.0 and LSS should have the advantage of generating minimal waste.
Lean concepts (such as TPM), Kanban, production smoothing, autonomation (or Jidoka), waste elimination, and Kanban and Andon)can be improved by integrating I4.0 technologies.
I 4.0 integration with LSS helps with forecasting and demand management over time.
Data generated with I4.0 will enable Lean and aid in measuring and subsequently improving key performance indicators
Six Sigma and Big data will help real-time quality control, event-based inspection, and predictive maintenance.
Six Sigma and Big data integration can help organizations to get better results.
LSS and Big data integration to benefit in all phases of DMAIC

4.2 Motivations for Integrating LSS and I4.0

There is a synergistic effect between Lean & I4.0, leading to improved Operational Performance (Buer et al., 2021; Ilangakoon et al., 2021; Felsberger *et al.*, 2020). Thus the synergistic effect between Lean & Industry 4.0 targets operational excellence by improving process flows and reducing bottlenecks (Moeuf *et al.*, 2018).

Indeed Lean manufacturing tools can also be facilitators or even prerequisites for a move towards Industry 4.0 (Buer et al., 2021; Chiarini and Kumar, 2020). The term Lean automation was coined by scholars with view that Lean and Agile systems can be embedded in I 4.0 approach (Chiarini, Belvedere and Grando,2020). They further argue that I 4.0 technologies can further improve the lean results. Similar, views were also expressed by Felsberger *et al.(*2020), wherein they stated the data generated by Industry 4.0 will help Lean to achieve greater performance. Kamble et al. (2020) found in a study on Industry 4.0 and Lean integration in Indian manufacturing facilities that Industry 4.0 technologies have a positive and direct influence on Lean and standard operating procedures. Thus, implementation of the future-oriented technologies of I4.0 makes a factory smart and supports organisations to overcome the barriers of Lean implementation. The reduction of product and process complexity through the Lean approach enables the economic and efficient use of Industry 4.0 technologies (Rosin *et al.*, 2020). When I4.0 technologies are integrated into the guidelines for designing a Lean

value stream, this approach benefits from the simplicity and efficiency of Lean with the ease and agility of the I4.0 technologies (Tortorella *et al.*, 2020). A point to be considered here is that some scholars have argued Lean can be seen as prerequisite for unlocking I4.0 potential (Chiarini, Belvedere and Grando,2020). Their fundamental line of thought rests on the argument of preventing automation of waste. Another view point expressed in some studies is I 4.0 technologies can further improve the lean (Felsberger *et al.*, 2020; Kamble et al,2020). Thus, we argue out clearly that motivating relationship between LSS 4.0 is not monodirectional, rather it represents a bidirectional relationship as depicted in the Figure 5.

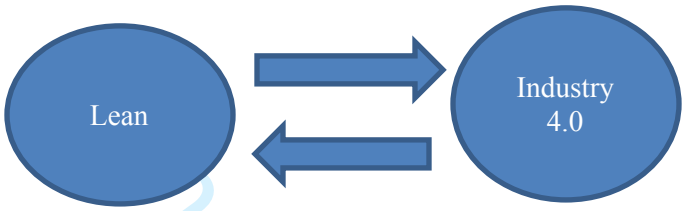

Figure 5: Bidirectional motivation relationship for organizations to implement I 4.0 and Lean

In terms of Six Sigma, there is no study yet indicating a clear gap to understand the motivation mechanism behind implementing I 4.0 and Six Sigma. However, scholars have examined how LSS and Big Data have been integrated. They suggest a mechanism by which how big data can aid LSS. They suggest that volume, variety, velocity, and veracity of big data and its applicability in modern LSS projects. However, concerns are also expressed in terms of big data in LSS such as "system design and integration, system performance, security and reliability of data, sustaining the control and conducting the experiments, distributed material and information flow"(Gupta, Modgil and Gunasekaran, 2020). We would like to argue here that Big data is just one aspect of I 4.0 and hence existing literature have not addressed the motivating relationship between LSS and I 4.0.

4.3 Challenges for Integrating LSS and I4.0

There is little guidance on how to integrate LSS and I4.0 (Vlachos *et al.*, 2021), so the integration is very much an evolving challenge to industry and practitioners. The question as to whether I4.0 and Lean manufacturing should be implemented concurrently or sequentially is ongoing. However, it is important to gain a more in-depth understanding of how these two domains interact before an implementation framework can be proposed (Buer, Strandhagen and Chan, 2018). Several technologies are combined within I4.0 including sensors, automation, robots, and cyber-physical systems. As a result of deploying these technologies change within operating procedures system and Lean standardised work may occur. The adaption of a production system to its environment incorporating new technologies and varying customer demands has to be investigated (Yin, Stecke and Li, 2018).Reyes, Mula and Díaz-Madroñero (2021) have discussed how recently, digital operations in the I4.0 context have generated new waste types such as non-utilised talent, poor information management, and poor supplier quality. These new waste types will need to be incorporated and understood along with the traditional 7 wastes. Tortorella, Giglio and van Dun (2019) found that socio-cultural changes delivered by Lean may conflict with the high levels of capital expenditure and

technological expertise demanded by I4.0. Thus, they stated that the duration of Lean implementation was significantly negatively correlated with technological intensity. While I4.0 will enhance knowledge management, workers on the shop floor need to be highly skilled in decision-making as the separation of dispositive and executive work diminishes with the implementation of I4.0 in a Lean environment (Hannola *et al.*, 2018). The integration of Lean and I4.0 needs reinvented mapping tools and implies a horizontal integration and a vertical, end-to-end integration within an organisation (Chiarini, 2020).As I4.0 and Lean have convergent and divergent characteristics (Buer et al., 2021), (Chiarini, Belvedere and Grando, 2020), it is important to understand which characteristics optimise deployment and integration of both. Rosin et al. (2020) found that softer Lean principles, which are more focused on communication between employees and creativity, do not seem to be subject to improvements by I4.0 technologies at this time. This is another factor that must be taken into account when integrating I4.0 with a Lean system. Other challenges are affecting Lean and I4.0 integration regarding the context in which the deployment takes place. The synergistic and complementary nature of LSS and I4.0 might change according to the context in which the deployment is taking place -for example, a developed vs developing economy (Tortorella, Giglio and van Dun, 2019). Thus, within different environments the integration and implementation of Lean & I4.0 may be stalled. Another point to consider is I 4.0 promotes flexible and collaborative systems and such a system may not be suitable for an agile and fast-changing lean environment (Chiarini, Belvedere and Grando,2020). They also state that some I 4.0 technologies could inhibit decision-making and problem-solving processes, especially among shop-floor workers. Very few researchers have discussed the impact of I4.0 on 'soft' LSS practices, the facilitating effect of Lean manufacturing on I4.0 implementation, empirical studies on the performance implications of an I4.0 and LSS manufacturing integration, the effect of environmental factors on the integration of I4.0 and Lean manufacturing, and an implementation framework for moving toward an I4.0 and LSS manufacturing integration (Tortorella *et al.*, 2020; Buer *et al.*, 2021). The roadmap towards I4.0 is complex and multifaceted, as manufacturers seek to transition towards new and emerging technologies whilst retaining operational effectiveness and a sustainability focus (Hughes et al., 2020). The table 4 depicts the summary of challenges.

Table 4: Summary of Challenges

No framework on how to integrate LSS and I4.0.
I 4.0 technologies may bring change within operating procedures of production system and Lean standardised work, there is no guidelines as regards to how to handle it.
Digital operations in the I4.0 context have generated new waste types such as non-utilised talent, poor information management, and poor supplier quality.
Socio-cultural changes delivered by Lean may conflict with the high levels of capital expenditure and technological expertise demanded by I4.0.
Workers on the shop floor need to be highly skilled in decision-making as the separation of dispositive and executive work diminishes with the implementation of I4.0 in a Lean environment.

Lean and I4.0 needs reinvented mapping tools due horizontal, vertical and end-to-end integration.
Softer Lean principles are not improved I4.0. technologies.
Lean and I 4.0 integration challenges are context dependant (e.g., developing / developed countries or type of sector).
Some I 4.0 technologies could inhibit decision-making and problem-solving processes, especially among shop-floor workers.
I 4.0 promotes flexible and collaborative systems and such a system may not be suitable for an agile and fast-changing lean environment
No studies on Six Sigma and I 4.0 integration challenges

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4.4 CSF's for Integrating LSS and I4.0

Continuous improvement/Lean management emerged as a critical success factor for the implementation of I4.0 in a study (Pozzi, Rossi and Secchi, 2021). This result may be debatable, because CI/Lean management can be viewed as a readiness factor for implementing I 4.0. Despite synergies between LSS and I4.0 the technologies may not aid improving operations if deployed in isolation in the absence of a Lean program (Kamble, Gunasekaran and Dhone, 2020). Kamble et al. (2020) found I4.0 technologies can positively effect operational performances but that effect is magnified when Lean manufacturing practices are present as a mediating variable. Thus, an established and successful Lean program is important to overcome any barriers to the implantation of I4.0 technology.

Lean practices help to install organisational habits and mindsets that favour systemic process improvements. While implementing Lean, companies must intelligently weigh the trade-offs when introducing novel technologies instead of simple standard operating procedures (Tortorella et al., 2020). Many authors discuss the importance of integrating Lean with I4.0 to ensure success. Deploying Lean management while improving certain Lean principles using Industry 4.0 technologies is a vital step in the integration of Lean and I4.0 (Rosin *et al.*, 2020). Lean practices need to be concurrently implemented with I4.0 to lead to larger performance improvements (Tortorella and Fettermann, 2018). LP and I4.0 favour simple decentralised frameworks, and implementing I4.0 can boost the outcomes of traditional LP implementation, resulting in distinguished performance levels (Tortorella, Giglio and van Dun, 2019).

As previously mentioned, the synergistic relationship between Lean and I4.0 is a benefit of and a motivation to the integration of Lean and I4.0 (Ilangakoon *et al.*, 2021). A proper foundation for the implementation of Lean concepts and I4.0 technologies can be achieved by focusing on the voice of the customer and employees (Ilangakoon *et al.*, 2021). The articles selected were more supportive and discursive in terms of the motivation of LSS and I4.0 integration. The researchers have not clearly distinguished between readiness factors and CSFs for LSS 4.0. There is no study either conceptual or empirical yet which clearly explicates the list of CSFs or readiness factors for LSS 4.0.

Nevertheless, there is a lack of literature around CSF's and challenges for LSS and I4.0 integration, as the topic is still emerging and there are only a handful papers are available in the existing literature.

5. Future Research Direction

This study has important implications for research practitioners in understanding state of the art in research towards LSS 4.0. This paper sets the foundation for LSS 4.0 research and identifies some of the research gaps which need to be addressed in the future via empirical studies. There are many future opportunities for research which include more longitudinal studies with organisations implementing LSS and I4.0 technologies to understand its impact on corporate performance. Moreover, a framework which combines LSS with I4.0 will be extremely useful to many LSS professionals in various types of organisations. Most of the studies on benefits of LSS and I 4.0 integration were on Lean and I 4.0 integration, there is a need for studies on LSS and I 4.0. The benefits of LSS 4.0 may also vary across the sector or type of organizations, hence future studies should empirically analyse the benefits of LSS 4.0 integration in manufacturing / service and SME's and LE's. Sustainability of benefits of LSS 4.0 is another area of research. Besides, the impact of LSS on emerging concept of Industry 5.0 in terms of people-centricity, resilience, and circularity and how it would impact the benefits would broaden the area of research LSS 4.0 research. In manufacturing segment Industry 4.0 technologies can be classified as front-end and base technology(Frank, Dalenogare and Ayala, 2019). The studies on impact of both front-end and base technologies on LSS and I 4.0 integration will help the organizations while implementing LSS 4.0, in terms of supportive and inhibitive technologies for I 4.0 and LSS integration. Most of the studies on motivation of LSS and I4.0 were conducted on Lean and I 4.0. The authors also suggest bidirectional motivation relationship as regards to Lean and I 4.0 implementation. Future studies should test this relationship empirically in different context and sectors. There was dearth of studies on motivation behind Six Sigma / LSS and I 4.0 integration. Though there were few studies on Six Sigma and Big data, however, the integration on Six Sigma and I 4.0 is lacking. This presents a new area of opportunity for researchers to unearth how variation can be reduced with I 4.0. To cite an instance Taguchi loss function does explicitly address mean and variation in the two-stage optimization approach in Robust Parameter Design methodology. It would be interesting to examine which factors may influence the process mean through I 4.0 technologies. Besides, how I4.0 technologies can help to bring them close to the target value while simultaneously reduce variation around the mean in a consistent manner will be an interesting area for variation reduction using technology. Further, we argue that variation reduction using technology will help the zero-defect manufacturing (ZDM). Also, it would be appropriate to examine which I 4.0 technologies can help in advancing with feedback / feedforward control in reducing variations drastically. In terms of challenges, there is dearth of articles on LSS and I 4.0 integration. This study finds that most of the studies have been carried on Lean and I 4.0. Hence, there is a need to explicitly study the challenges of integration of Six Sigma / LSS with I 4.0. Without understanding the challenges, it would be difficult for organizations to practically implement LSS and I 4.0 integration in their organizations. This study also finds dearth of literature on LSS and I 4.0. There were few studies on Lean and I 4.0, however, in the said study the authors failed to distinguish clearly between

readiness factor and CSFs. Therefore, there is a need for a future study which clearly explicates what are the readiness factors and CSFs for LSS 4.0.

6. Conclusion

The current and future evolution of I4.0 proves that LSS is not obsolete but has a role in integrating I4.0 technologies for improved operational performance. Lean Six Sigma has evolved to incorporate I4.0 technologies.

Within the SLR search, conference papers were part of the exclusion criteria and might be a potential source of current research around LSS and I4.0 integration. This implies some of the latest and original ideas might have not been considered in the SLR. Qualitative and quantitative studies with professionals working on LSS and organisational digitalisation programs would be an opportunity to leverage further learnings around this new evolution of LSS 4.0.

A limitation of the study is the lack of research in this area as it is an emerging area. Very few articles discussed the impact of I4.0 on 'soft' LSS practices, and there were few empirical studies on the performance implications of an I4.0 and LSS integration. In other words, the true impact of the integrated approach of LSS with I4.0 is not known to many researchers and this is a major gap in the current literature.

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