Mapping the Terrain for Lean Six Sigma 4.0

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Abstract. Lean Six Sigma is a powerful methodology that integrates the best of two distinct approaches to business excellence: Lean and Six Sigma. While Six Sigma focuses on the systematic reduction of variation within processes, the Lean approach aims for business growth through waste elimination and the continuous development of people. Given the advent of Industry 4.0, digitalization now presents the next frontier of industrial improvement. Lean Six Sigma can be integrated with Industry 4.0 to optimize process efficiency. This study is a systematic literature review on the integration of Industry 4.0 and Lean Six Sigma. The findings are that while this topic is an emerging area of study, there are benefits, motivations, critical success factors, and challenges to integrating Lean Six Sigma and Industry 4.0.

Keywords: Lean Six Sigma, Industry 4.0, Continuous Improvement.

1 Introduction

The advent of the first Industrial Revolution transitioned production from craft production into mass production and from mass production into Lean production and Lean supply chains. Lean production is a philosophy that focusses on understanding the deeper underlying causes of waste to create more customer value. It has also been recognized as a methodology for operational excellence globally. Lean has been integrated with Six Sigma in recent years firstly by George in 2002 and subsequently adopted in its first evolution as Lean Six Sigma (LSS) by industry and academics (Lean Six Sigma 1.0). The integration has benefits with the combination resulting in both waste reduction and variation reduction [1].

In recent years Lean has been coined with "Green", and this has progressed Lean thinking into the 2nd iteration of its evolution (Lean Six Sigma 2.0). Historically, profitability and efficiency objectives have been the prevailing interest for organisations in deploying Lean Six Sigma. However, the move towards green operations has forced companies to seek alternatives to combine these with green objectives and initiatives[2, 3]. While some literature in relation to Lean and Green can be traced

back to 1994 in which Davids wrote about Lean and Green [4] , the Lean Six Sigma 2.0 “Green” evolution did not really take off in practice until after 2001 [2, 5–7]. LSS can contribute toward greater environmental sustainability [7].

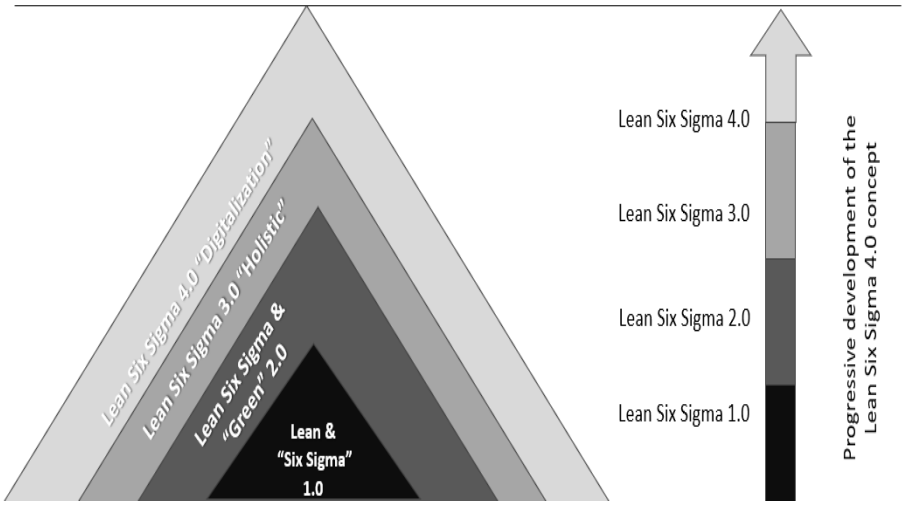

Figure 1: Progressive development of the Lean Six Sigma 4.0 concept “sand cone” -Authors own derivation.

The ”*holistic*” approach of Lean Six Sigma was first touted by Snee and Hoerl as early as 2005-2007 [8–10, 11] in various journal and conferences. However their new paradigm for Lean Six Sigma as a holistic approach was first put forward in their book “*Leading Holistic Improvement with Lean Six Sigma 2.0*” in 2018 [12]. Snee and Hoerl called the holistic approach the 2nd evolution of LSS in their book. The authors of this research paper have put forward that as the holistic approach has come after the LSS Green iteration and evolution of Lean Six Signa; the holistic approach is therefore LSS 3.0. The definition of the LSS 3.0 approach put forward by this research is based on Snee and Hoerls definition is “*An Improvement system that can successfully create and sustain significant improvements of any type, in any culture and in any business*” [12]. Further the holistic approach allows for 1. the integration of a wide set of methods so that the most appropriate methods can be adapted to tackle a problem and 2. a deployment system like LSS to create and sustain improvements [8].

However, as traditional manufacturing evolves into digitalization with the implementation and advent of Industry 4.0 (I4.0) technologies, Lean has become digitally enabled[13]. Thus, there is a new evolution of Lean 4.0 -digitalization. The advance

of new Industry 4.0 technologies such as the Internet of Things (IoT), big data and data analytics, additive manufacturing, 3D printing, advanced robotics, augmented and virtual reality, cloud computing, simulation, machine learning and artificial intelligence are increasing production and service complexity [14, 15]. Both paradigms of LSS and I4.0 are promising to solve future challenges in manufacturing. The integration of I4.0 technologies into the guidelines for designing a lean value stream raises a distinct approach that benefits from the simplicity and efficiency of Lean Production with ease and agility of the technologies typical of the Fourth Industrial Revolution [4].

The Sand Cone model (Figure 1) which describes the cumulative enhancement of capabilities as described by Ferdows and De Meyer in 1990 demonstrates the four Lean stages or evolutions [16]. Each hierarchical evolution enhances and leads to a cumulate evolution of Lean Six Sigma capabilities from Lean Six Sigma 1.0 right through to Lean Six Sigma 4.0. However, the integrated effect of Industry 4.0 technology and Lean manufacturing practice on SOP has not been empirically investigated [17, 18].

Hence, the question arises if and how these developments can possibly support each other. Thus, this paper aims to contribute to this research area.
Thus, a series of research questions arise:

- How does LSS integrate with I4.0?
- What are the motivations for integrating LSS and I4?
- What are the benefits of integrating LSS & I4.0?
- What are the critical success factors (CSF's) to integrating LSS and I4.0?

2 Methodology – Systematic Literature Review

A systematic literature review (SLR) was utilized. The authors searched systematically for articles published between 2011 and 2021, using the following full academic databases Web of Science and Scopus. The search strategy followed Tranfield et al.'s (2003) approach, which seeks to create a reliable knowledge stock by synthesizing the relevant body of literature [19]. Firstly, the emphasis on the systematic process of literature search, extraction and synthesis are higher in SQLRs than in other forms of review, making the work more scientific and replicable [20] [19]. The following search string was applied to search all the databases mentioned above: "Lean " AND "Industry 4.0", "Six Sigma" AND "Industry 4.0" and "Lean Six Sigma" AND "Industry 4.0". Table 1 provides a detailed listing of the inclusion/exclusion criteria. The references of the selected studies were manually checked to identify additional relevant studies that were missed in the database search. Grey literature (conference papers, magazine-related articles, workshops, books, editorials, prefaces) were excluded.

Table 1. Inclusion & Exclusion criteria for the SLR

Inclusion criteria	Exclusion criteria
Academic peer-reviewed journal articles books, magazine-related articles, etc.) related to Lean, Six Sigma and/or LSS and I4.0	Grey literature (conference proceedings, dissertations, text
Articles published in high quality journals ABS Ranked 3 and 4*	Articles published in languages other than English
Articles published from 2011 to 2021	Articles published before 2011 as the term Industry 4.0 was only coined in 2011
	Articles published in non-refereed journals

A flowchart was utilized to map the SLR steps, as outlined in Figure 2. The initial search identified 2,357 articles. Duplicates were firstly removed, and the full text was retained if the abstracts stated that the study was related to Lean, Six Sigma and LSS and its application in an Industry 4.0 context. The three authors acted as reviewers and independently assessed the inclusion eligibility of the retrieved studies based on the search criteria[21]. Inclusion agreement was solved by discussions and consensus among reviewers.

Additionally, studies that were not published in peer-reviewed journals or were under 3 or 4 in the ABS journal ranking of 2018 [22] were also excluded. This process yielded 355 studies for final inclusion at this stage of the review.

The data collation was managed utilizing Zotero and MS Excel spreadsheets to record information concerning the articles selected; the authors independently reviewed each paper and coded them using a meta-framework. Once the final articles were extracted and recorded, coding was completed in order for errors to be minimized. The analysis proceeded under various characteristics in response to the research questions, including 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. With the help of the proposed methodology, the authors filtered out 19 relevant research papers for in-depth exploratory analysis of LSS & I4 integration. The insights of these publications were summarized through reviewing patterns of publications and emerging themes.

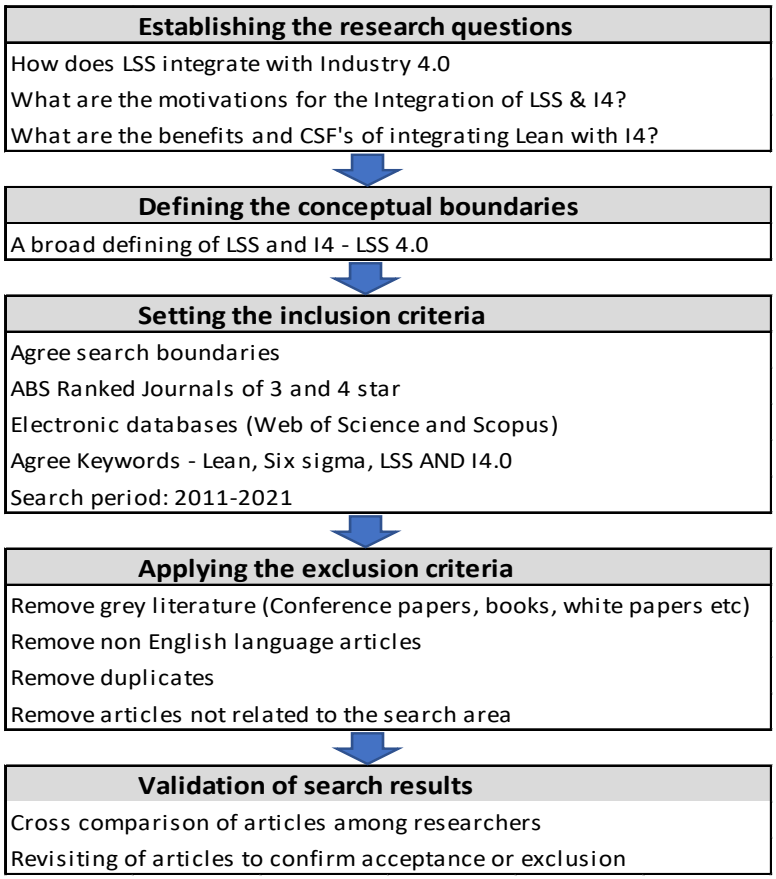

Figure 2. A summary of evidence search and selection

3 Results

The final selected journals were analyzed by journal type and years of publication. Lean Six Sigma and I4.0 are still considered an emerging research area, and this fact was verified by the relatively small number of 19 final selected articles (Table 2).

Table 2: Final Selection of articles from SLR review

Year	Authors	Titles	Journal
2020	Buer, S.-V., Semini, M., Strandhagen, J.O., Sgarbossa, F.	The complementary effect of lean manufacturing and digitalisation on operational performance	International Journal Of Production Research
2018	Buer, S.-V., Strandhagen, J.O., Chan, F.T.S.	The link between industry 4.0 and lean manufacturing: Mapping current research and establishing a research agenda	International Journal of Production Research
2020	Ciano, M.P., Dallasega, P., Orzes, G., Rossi, T.	One-to-one relationships between Industry 4.0 technologies and Lean Production techniques: a multiple case study	International Journal Of Production Research
2020	Chiarini, Belevdere, 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
2019	Felsberger, A., Qaiser, F.H., Choudhary, A., Reiner, G. Andreas Felsberger, Fahham Hasan Qaiser, Alok Choudhary & Gerald Reiner	The impact of Industry 4.0 on the reconciliation of dynamic capabilities: evidence from the European manufacturing industries	Production Planning & Control
2019	Laurie Hughes, Yogesh K. Dwivedi, Nripendra P. Rana, Michael D. Williams & Vishnupriya Raghavan	Perspectives on the future of manufacturing within the Industry 4.0 era	Production Planning & Control
2018	Hannola, L., Richter, A., Richter, S., Stocker, A.	Empowering production workers with digitally facilitated knowledge processes–a conceptual framework	International Journal Of Production Research
2020	Kamble, S., Gunasekaran, A., Dhone, N.C.	Industry 4.0 and lean manufacturing practices for sustainable organisational performance in Indian manufacturing companies	International Journal Of Production Research
2021	Giulio Marcucci, Sara Antomarioni, Filippo Emanuele Ciarapica & Maurizio Bevilacqua	The impact of Operations and IT-related Industry 4.0 key technologies on organizational resilience	Production Planning & Control
2021	Rossella Pozzi, Tommaso Rossi & Raffaele Secchi	Industry 4.0 technologies: critical success factors for implementation and improvements in manufacturing companies	Production Planning & Control
2017	Alexandre Moeuf, Robert Pellerin, Samir Lamouri, Simon Tamayo-Giraldo & Rodolphe Barbaray	The industrial management of SMEs in the era of Industry 4.0	International Journal of Production Research
2020	Núñez-Merino, M., Maqueira-Marín, J.M., Moyano-Fuentes, J., Martínez-Jurado, P.J.	Information and digital technologies of Industry 4.0 and Lean supply chain management: a systematic literature review	International Journal Of Production Research
2020	Rosin, F., Forget, P., Lamouri, S., Pellerin, R.	Impacts of Industry 4.0 technologies on Lean principles	International Journal of Production Research
2020	Sahu A.K., Padhy R.K., Dhir A.	EPEC 4.0: an Industry 4.0-supported lean production control concept for the semi-process industry	Production Planning & Control
2020	Tortorella, G.L., Pradhan, N., Macias de Anda, E., (...), Sawhney, R., Kumar, M.	Designing lean value streams in the fourth industrial revolution era: proposition of technology-integrated guidelines	International Journal Of Production Research
2018	Tortorella, G.L., Fettermann, D.	Implementation of Industry 4.0 and lean production in Brazilian manufacturing companies	International Journal Of Production Research
2019	Tortorella, GL; Giglio, R; van Dun, DH	Industry 4.0 adoption as a moderator of the impact of lean production practices on operational performance improvement	International Journal Of Operations & Production Management
2017	Yin, Y., Stecke, K.E., Li, D.	The evolution of production systems from Industry 2.0 through Industry 4.0	International Journal Of Production Research

The majority of the final selection came from 3 main journals (Figure 3) – the International Journal of Production Research (42%), Production Planning and Control (37%) and the International Journal of Operations & Production Management (5%). It was not surprising that LSS 4.0 is still very much an emerging area of research as several authors who have written about the topic have had similar findings [23, 24]. Also, article analysis by year of publication demonstrated that LSS 4.0 has emerged as a topic of researcher interest only from 2017 onwards.

Very few articles discussed the impact of Industry 4.0 on (1) 'soft' lean practices, (2) the facilitating effect of lean manufacturing on Industry 4.0 implementations, (3) empirical studies on the performance implications of an Industry 4.0 and lean manufacturing integration, (4) the effect of environmental factors on the integration of Industry 4.0 and lean manufacturing, and (5) implementation framework for moving toward an Industry 4.0 and lean manufacturing integration [23, 24]

Some authors under the SLR study and had more than one publication on the theme of LSS & Industry 4.0 integration. These authors included Tortorella (Brazil), who had three articles, Buer (Norway), Strandhagan (Norway), Chiarini (Italy) and Kumar (UK), whom all had published two research articles.

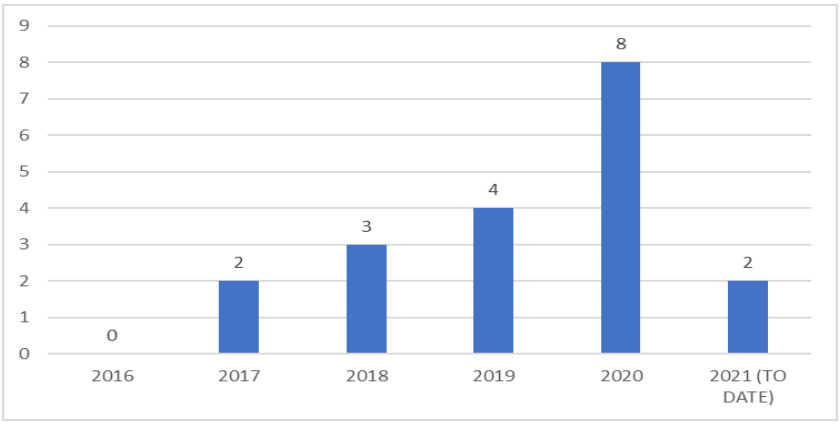

Figure 3 – Breakdown of publication by year in the LSS & I4 area

The articles selected were screened and themes noted under various categories and themes such as the benefits of LSS & I4 integration, the motivations for LSS & I4 integration, the challenges of LSS & I4 integration, and finally, the CSFs for LSS & I4 integration. These common themes were summarized in table 3. All articles selected were unanimous in the support or the benefits of integrating Lean and Industry 4.0. There were fewer articles that discussed the CSF's for and challenge to integrating LSS and Industry 4.0.

Table 3: Themes emerging around Lean Six Sigma 4.0 after SLR of the final selection of articles

Cited article	Benefits of intregrating Lean Six Sigma & Industry 4.0	Motivations for intregrating Lean Six Sigma & Industry 4.0	Challenges of intregrating Lean Six Sigma & Industry 4.0	Critical Success Factors for integrating Lean Six Sigma & Industry 4.0
Sven-Vegard Buer, Marco Semini, Jan Ola Strandhagen & Fabio Sgarbossa (2021)	X	X	X	X
Sven-Vegard Buer, Jan Ola Strandhagen & Felix T. S. Chan (2018)	X	x	X	X
Maria Pia Ciano, Patrick Dallasega, Guido Orzes & Tommaso Rossi (2021)	X			
Andrea Chiarini, Valeria Belvedere & Alberto Grando (2020)	X	X		
Andrea Chiarini & Maneesh Kumar (2020)	X	X		X
Andreas Felsberger, Fahham Hasan Qaiser, Alok Choudhary & Gerald Reiner (2020)	X	X		
Laurie Hughes, Yogesh K. Dwivedi, Nripendra P. Rana, Michael D. Williams & Vishnupriya Raghavan (2020)	X		X	
Lea Hannola, Alexander Richter, Shahper Richter & Alexander Stocker (2018)	X	X		
Sachin Kamble, Angappa Gunasekaran & Neelkanth C. Dhone (2020)	X	X	X	X
Giulio Marcucci, Sara Antomarioni, Filippo Emanuele Ciarapica & Maurizio Bevilacqua (2021)	X			
Rossella Pozzi, Tommaso Rossi & Raffaele Secchi (2021)	X			
Alexandre Moeuf, Robert Pellerin, Samir Lamouri, Simon Tamayo-Giraldo& Rodolphe Barbaray (2017)	X	X		
Miguel Núñez-Merino, Juan Manuel Maqueira-Marín, José Moyano-Fuentes & Pedro José Martínez-Jurado (2020)	X	X	x	X
Frédéric Rosin, Pascal Forget, Samir Lamouri & Robert Pellerin (2020)	X	X	X	X
Philipp Spenhoff, Johan C. (Hans) Wortmann & Marco Semini (2021)	X			
Guilherme Luz Tortorella, Ninad Pradhan, Enrique Macias de Anda, Samuel Trevino Martinez, Rupy Sawhney & Maneesh Kumar (2020)	X	X	X	
Guilherme Luz Tortorella & Diego Fettermann (2018)	X			
Tortorella, G.L., Giglio, R. and van Dun, D.H. (2019)	X	X	X	X
Yong Yin, Kathryn E. Stecke & Dongni Li (2018)	X	x		

4. Discussion

According to the literature reviewed as part of this SLR, there is a strong rationale for integrating LSS and I4.0 in terms of benefits for integration and motivations for integration. There are also challenges to integrating and critical success factors (CSF's) of integrating LSS and I4.0. Lean practices are positively associated with Industry 4.0 technologies, and their concurrent implementation leads to larger performance improvements [14]. The integration of I4.0 technologies into the guidelines for designing a lean value stream raises a distinct approach that benefits from the simplicity and efficiency of Lean Production with the ease and agility of the technologies typical of the Fourth Industrial Revolution [12, 13]. I4.0 and Lean practices complement I4.0 technologies [12], and there is a synergistic effect between both to target operational excellence [12],[26].

Lean manufacturing tools can also be facilitators or even prerequisites for a move towards Industry 4.0. Industry 4.0's technologies are improving the implementation of Lean. Lean principles, depending on the technologies' capability levels. I4.0 technology can support strong integration of Just-in-time and Jidoka [27, 28]. While technologies from Industry 4.0 do not seem to cover the integrated nature of Lean principles overall, they can reinforce the efficiency of these principles. Lean practices tend to be more impactful with Industry 4.0 as it allows a better understanding of customers' demands and accelerates information sharing processes. Real-time integration with minimal waste generation is an advantage [18]. Buer et al. especially highlighted that total productive maintenance (TPM), Kanban, production smoothing, autonomation, waste elimination, and Kanban and Andon could be improved by I4.0 technology[25]. However, I4.0 demonstrates little or no support for waste reduction via people and teamwork. Softer Lean principles such as these, which are more focused on communication between employees and creativity, do not seem to be subject to improvements by Industry 4.0 technologies at this time [27]. In terms of Industry 4.0 alignment with the Lean Toyota production system, flow line, job shop, cell, flexible manufacturing system, and seru –I4.0 can be integrated and applied to the different production types to match different demand dimensions over time [14]. Big data collection and evaluation for Lean production and TPS should become easier because of IoT. KPI data generated from I4.0 will enable Lean [29].

There are challenges to integrating Lean and I4.0. While there are synergies between the two, I4.0 technologies may not contribute to improved operational excellence if implemented as a standalone application in the absence of Lean practice, according to Kamble et al. in his 2020 study [24]. The study findings indicate that while I4.0 technology has a direct and positive effect on operational performance, this effect is magnified in the presence of Lean manufacturing practices as a mediating variable. In summary, the successful implementation of Lean practices are crucial for overcoming I4.0 technology implementation barriers. Industry 4.0 and Lean have convergent and divergent characteristics [25], [15]. The synergistic and complementary nature of LSS and I4.0 might change according to the context in which the de-

ployment is taking place -for example, a developed vs developing economy[18]. Integration and implementation of these concepts can therefore be slower. Lean is focused on developing human integration, which is crucial for overcoming the I4.0 technology implementation barriers. Thus the successful implementation of Lean enables organizations to initiate the implementation process for Industry 4.0 technology [17].

Due to Industry 4.0 and Lean's convergent and divergent characteristics. Lean entails socio-cultural changes that are stimulated daily through fast and simple workfloor experimentations, which may conflict with the high levels of capital expenditure and technological expertise demanded by Industry 4.0 [18].

Industry 4.0 combines many technologies such as sensors, automation, robots, and cyber-physical systems. These technologies may require changing the operational procedures of a production system and Lean SOP's, and standardized work. How a production system adapts to an environment with new technologies and customer demand dimensions has to be investigated [28].

The CSF's to integrating Lean and I4.0 are many. There is a clear need to pursue the deployment of Lean management while improving certain Lean principles using Industry 4.0 technologies[27]. The roadmap towards Industry 4.0 is complex and multifaceted, as manufacturers seek to transition towards new and emerging technologies whilst retaining operational effectiveness and a sustainability focus[29].

Lean practices help to install organizational habits and mindsets that favor systemic process improvements. While implementing Lean, companies must intelligently weigh the trade-offs when introducing novel technologies instead of simple standard operating procedures [23]. 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[30]. 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 organization [31]

The articles selected were more supportive and discursive in terms of the motivation of Lean and I4.0 integration. It is clear that there is a dearth of literature around Lean and I4.0 CSF's and challenges as the area is still an emerging and unknown one.

5. Conclusion

In light of the upcoming fourth industrial revolution, the researchers find that Lean is not obsolete but rather is more important than ever to reap the benefits from emerging Industry 4.0 technologies and integrate with them for improved operational performance. A limitation of the study is the lack of research in this area as it is an emerging area. Also, within the SLR conference papers were excluded and may perhaps have been a source of further research around Lean and Industry 4.0 integration. Future research opportunities include more longitudinal studies on organizations implementing Lean, LSS and Industry 4.0 type technologies to ascertain and benchmark the benefits, CSF's and other learnings. Qualitative and quantitative studies with profes-

sionals working on Lean and organizational digitalization programs would be an opportunity to leverage further learnings around this new evolution of Lean 4.0.

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