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Industry 5.0's Pillars and Lean Six Sigma:

Mapping the Current Interrelationship and Future Research Directions

Abstract

Purpose

In the evolving landscape of Industry 5.0 (I5.0), which emphasises sustainability, human-centricity, and resilience, the role of Lean Six Sigma (LSS) methodology remains underexplored. Our study addresses this gap by examining the potential of LSS to support I5.0 while identifying areas for further investigation.

Design/methodology/approach

This study's multifaceted approach, which includes systematic literature review, bibliographic network analysis, and expert validation, provides a holistic exploration of the interaction between LSS and I5.0 as the basis for well-founded conclusions.

Findings

The analysis yields several valuable insights. Firstly, it demonstrates the absence of a direct link between LSS and I5.0. Secondly, the substantial body of literature analysed establishes connections between LSS and its pillars. Thirdly, the analysis identifies points of intersection, difference, and similarity between LSS and I5.0, highlighting the potential of LSS to facilitate implementation of I5.0 through its proven methodologies, continuous improvement culture, risk management, error learning, human-machine collaboration, and training and skill development.

Originality

This study pioneers the effort to realise the latent potential of LSS in the context of I5.0. Its systematic identification of the synergies between these paradigms fills a critical gap in the literature and gives policymakers, managers, and researchers a guide for informed decision-making to maximise the benefits of I5.0 for individuals, companies, society, and the planet.

Keywords

Industry 5.0; Lean Six Sigma; sustainability; human-centrism; resilience; Industry 4.0.

Article classification

Literature review

1. Introduction

Throughout the evolution of industry, critical shifts have marked significant turning points, or revolutions (Coelho *et al.*, 2023). In recent years, the term Industry 5.0 (I5.0) has emerged to link those who believe in people's power to create innovations and those who connect innovations to new ideas to solve complex problems in the global economy (Anatan, 2020).

The I5.0 paradigm recognises industry's power to achieve societal goals beyond jobs and growth. It seeks to make industry a resilient provider of prosperity by ensuring that production respects our planet's limits and placing workers' well-being at the centre of the manufacturing process in a harmonious symbiosis of humans and machines (Breque *et al.*, 2021).

Shifting emphasis from solely shareholder value to stakeholder value, I5.0's vision is based on three pillars: sustainability, human-centrism, and resilience (Madsen and Berg, 2021). The concept of sustainability includes the triple-bottom-line social, economic, and environmental dimensions (Batwara *et al.*, 2024), and entails responsible stewardship of resources to meet the needs of present and future generations while respecting planetary limits (Griggs *et al.*, 2013). Human-centrism stresses the imperative of nurturing work environments that prioritise workers' well-being and empowerment (Breque *et al.*, 2021). Resilience in the face of disruptions underscores systems' capacity to recover and adapt (Zhang and Van Luttervelt, 2011).

The emergence of a new paradigm such as I5.0 necessitates a robust roadmap and effective tools to ensure successful implementation. Among methods of continuous improvement in organisational management, Lean Six Sigma (LSS) stands out as a standard for efficiency and quality in the industrial landscape (Elkhairi *et al.*, 2022). The LSS framework for organisational improvement (Pepper and Spedding, 2010) has demonstrated its robustness over many decades, and according to Adams (2021), approximately 69.7% of manufacturers utilise some form of LSS practice.

The goal of this study is to analyse the LSS methodology's potential for successful implementation of I5.0 and its pillars. To this end, we propose research questions to determine possible connections and differences between LSS and I5.0 both together and separately, considering the pillars on which I5.0 is based. This approach enables us to assess whether LSS is a valid tool for implementing I5.0 and to identify the aspects with the greatest potential to achieve the desired results.

Following this introduction, Section 2 proposed the research questions raised by these paradigms. Section 3 defines the methodology. Section 4 reviews the literature to map the theoretical landscape. Section 5 synthesises the expert insights gained. Section 6 details the findings, and Section 7 presents the study's contributions and outlines paths for future research.

2. Research questions

Despite the individual merits of I5.0 and LSS, the interaction between them remains largely unexplored, with many researchers calling for further study of their integration. Moraes *et al.* (2023), for example, stress the need to deepen integration of LSS and I5.0. Puram and Gurumurthy (2021) recommend that future studies explore the integration of LSS with emerging topics. Rahardjo *et al.* (2023) view research on this integration as important to enabling organisations to thrive amid dynamic challenges and opportunities, while Rossi *et al.* (2022) highlight the need to better understand the impacts of LSS on I5.0 and these

paradigms' points of intersection. Finally, for Antony *et al.* (2023), the lack of an approach that integrates LSS with I5.0 is a major gap in the current literature.

Our study seeks to fill this gap by determining the interconnectedness and potential synergies between these paradigms, clarifying their shared objectives and distinguishing features, and establishing pathways by which LSS can foster I5.0. Determining whether LSS can effectively support I5.0 implementation requires assessing the extent of the links between the two concepts. Only so can we determine their potential synergies. As not all elements of each model align, analysing where they intersect and diverge, work together or conflict is crucial to determining challenges or incompatibilities that affect successful implementation and thus achievement of the I5.0 vision. We propose the following research questions to advance academic knowledge that informs strategic decision-making in businesses:

RQ1: Are the I5.0 paradigm and LSS methodology inherently connected?

RQ2: What are the key intersections between LSS and I5.0?

RQ3: How do LSS and I5.0 differ in their approaches and objectives?

RQ4: In what ways can LSS facilitate realisation of I5.0 vision?

To make the previous research questions more concrete, we analyse the potential role of LSS in implementing and enhancing each of the three pillars of I5.0. Determining the impact of LSS on each pillar enables us to determine LSS's impact on the whole. We therefore propose the following research questions:

RQ5: How does LSS enhance sustainability within I5.0?

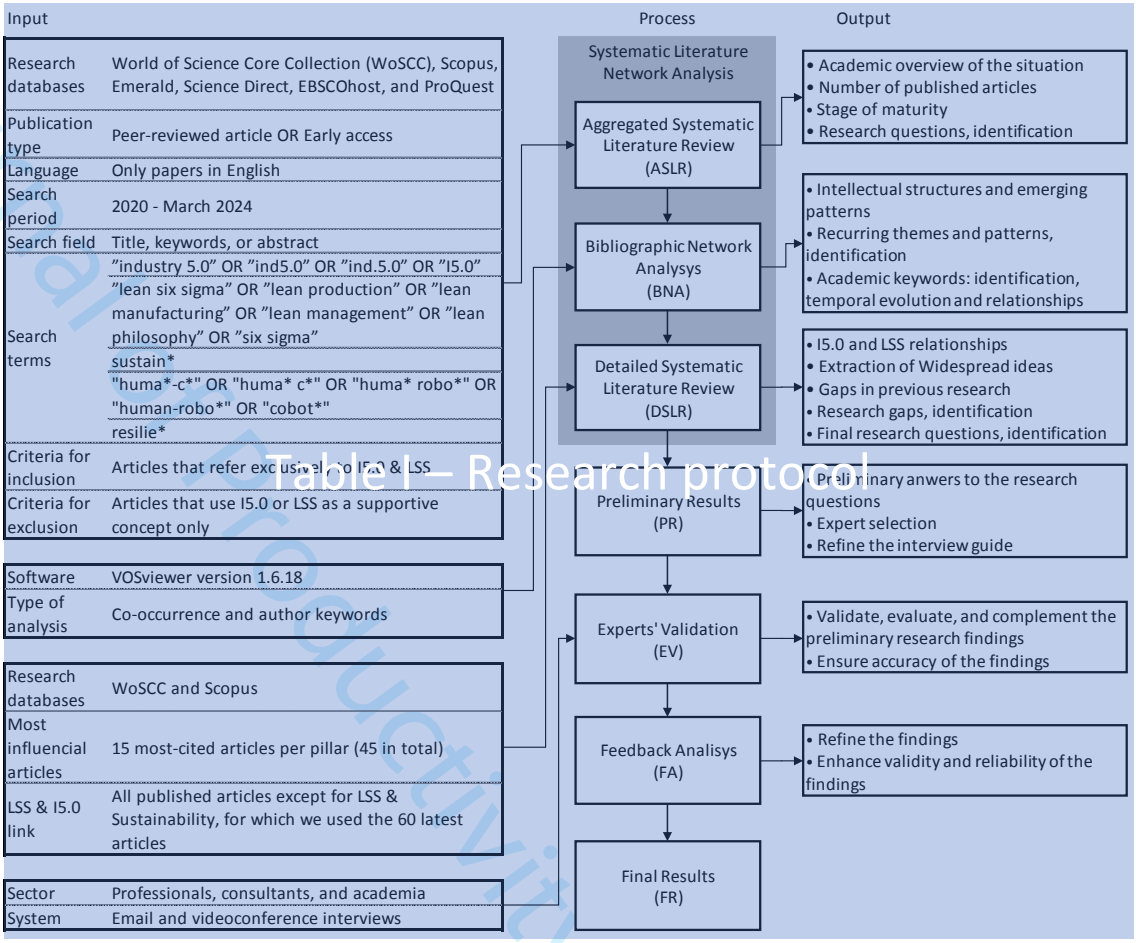
RQ6: How does LSS foster human-centricity in alignment with I5.0?

RQ7: How does LSS bolster organisational resilience in the context of I5.0?

3. Methodology

This study adopts the dynamic methodology of Systematic Literature Network Analysis (SLNA), which combines Systematic Literature Review (SLR) with quantitative Bibliographic Network Analysis (BNA), using modern bibliometric tools to detect emerging topics and their dynamic evolution (Khitous *et al.*, 2020). This approach suits our study's interdisciplinary nature and focus on emerging topics (Ejsmont *et al.*, 2020). Table I summarises the research protocol, including the inputs, process, and outputs.

Table I - Research protocol flowchart



An **Aggregate Systematic Literature Review (ASLR)** grounds its analysis by gathering existing knowledge and assessing the current state of the field (Kunisch *et al.*, 2018). Such review is crucial to advancing knowledge, as it aids in theory development, consolidates areas on which abundant research has been performed, and identifies areas requiring further research (Webster and Watson, 2002). The search output in our study determined the number of published articles, facilitated evaluation of the field's stage of maturity, and contributed to initial identification of unanswered research questions (Kraus *et al.*, 2020).

We used **Bibliographic Network Analysis (BNA)** to identify co-occurrences among authors' keywords and summarise the intellectual structure, emerging trends, recurring themes, and patterns in the field (Bhatt *et al.*, 2020). The BNA provided insights into the current state of knowledge, its temporal evolution and relationships, and the research questions that need to be addressed. These insights informed subsequent discussions.

After ASLR and BNA, we conducted a **Detailed Systematic Literature Review (DSLR)** to identify the relationships between I5.0 and LSS. This process involved extracting the most common ideas, identifying gaps in previous research, establishing the final research questions, and synthesising the literature related to these questions. We selected the 15 most-cited papers for each pair of terms (45 in total) from which to extract the most widespread ideas. Previous studies justify this approach (e.g., Barley *et al.* (2017) and Endo *et al.* (2014)). To answer the research questions, we analysed all published articles linking I5.0 to LSS except those on LSS & Sustainability, for which we reviewed only the 60 latest articles. We included both WoSCC and Scopus, as they are the databases most used in

terms of citations to define the field. These databases also lead in scholarly impact, index high-quality journals (Pranckutė, 2021), and contain the most articles. Finally, 87% of WoSCC's articles were also found in Scopus, and we excluded articles only marginally related to the subject matter through data curation. This review enabled us to obtain the **Preliminary Results (PR)**.

Expert Validation (EV) involved collaborating with experts in both I5.0 and LSS, as recommended by Beecham *et al.* (2005). Engaging experts in the evaluation process enhanced the rigour, evidence base, and practicality of the results for real-world scenarios (Picardi and Masick, 2014). The novelty of I5.0 made this collaborative endeavour challenging, however, due to the limited availability of experts with comprehensive knowledge in both fields.

From the academic databases and other publications, we assembled an international panel of experts who specialised in different branches of knowledge. They were from Brazil (2), Egypt (1), Iran (1), Poland (2), Portugal (2), Spain (3), and Taiwan (1). The panel was composed of four professionals, two consultants, and six academics. This sample size is common in the field, particularly in the early stages of research (Hakim, 1987), and similar approaches have been used in numerous prior studies. Dybå (2000), for example, engaged 11 experts for a similar review. The experts' feedback was subsequently collected through email exchanges and videoconference interviews of around 45 minutes each. After the EV, the authors conducted a Feedback Analysis (FA) and integrated the valuable information provided by the experts to propose the Final Results (FR). The purpose of all these steps was to improve the robustness of the study's results.

Following our description of the methodology here, Section 4 presents our examination of the Systematic Literature Network Analysis, comprised of ASLR, BNA, and DSLR.

4. Systematic Literature Network Analysis

To outline the current state of research, we initially conducted an ASLR to count the articles published. Table II summarises the findings.

Table II - Number of articles

	WoS	Scopus	Emerald	ScienceDirect	EBSCOhost	ProQuest
Industry 5.0	652	744	307	240	303	356
LSS	8192	9673	465	1849	4322	6868
LSS & Industry 5.0	36	12	2	2	1	3
LSS & Sustainable	1009	1445	110	276	553	651
LSS & Human-Centric	46	66	20	11	19	8
LSS & Resilient	71	63	14	23	30	39

Table II - Number of articles

As per Kraus *et al.* (2020), the results of our analysis indicate that the field of I5.0 is in its nascent stage, with several research questions still unanswered. This assessment corroborates the assertion by Ivanov (2022) that comprehensive understanding and conceptualisation of I5.0 across management, organisations, and technological perspectives has yet to be fully achieved. LSS, in contrast, emerges as a relatively mature field with fewer unresolved questions. Fusion of these two fields is in the early stages, with numerous avenues for further investigation.

Despite the limited number of publications on I5.0, a notable trend emerges with a steady growth rate of 190% in publications during the years 2021-2024. This upward trajectory

signifies increasing interest in and scholarly attention to I5.0, underscoring its emergence as a significant area of inquiry.

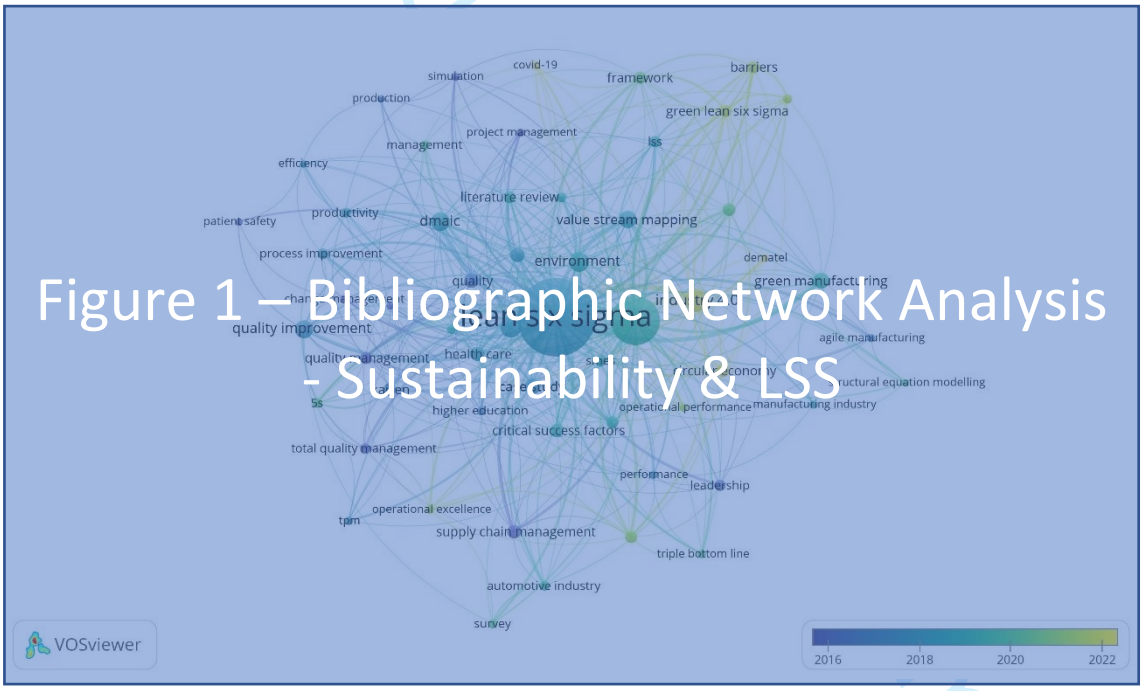
Subsequent sections of this study examine the interrelation between the foundational pillars of I5.0 and LSS.

Sustainability & LSS

The literature review identified a total of 1620 articles on this relationship (851 articles common to both databases, 594 found only in Scopus, and 175 found only in WoSCC). Analysis of the 15 most-cited articles on the intersection of LSS practices with sustainability objectives yielded valuable insights into the interrelation between these two paradigms.

The BNA (Figure 1) revealed a robust linkage between LSS and sustainability, with a value of 1591. These concepts are linked predominantly to terms such as Industry 4.0, continuous improvement, green manufacturing, and quality enhancement. A total of 428 links were identified and grouped into eight clusters, each of which represented dimensions of environmental, social, and economic aspects of sustainability. The analysis also indicated a research trend shifting towards emerging concepts such as Industry 4.0, circular economy, green LSS, and operational excellence.

Figure 1 – Bibliographic Network Analysis - Sustainability & LSS



Summarising the DSLR, Yang *et al.* (2011) and King and Lenox (2001) exemplify studies demonstrating a positive association between LSS practices and environmental management, highlighting potential to reduce waste and pollution. Cherrafi *et al.* (2017), and Piercy and Rich (2015) extended knowledge of the broade sustainability benefits of LSS operations, including lower resource consumption and improved energy efficiency. Cai *et al.* (2019) proposed a new concept—Lean Energy-Saving and Emissions-Reduction—and demonstrated its effectiveness in promoting sustainability. Furthermore, Dues *et*

al. (2013) evaluated the relationship and links between LSS and green supply chain management practices to demonstrate that LSS benefits green practices.

This DSLR indicates that the most widespread ideas are strongly and positively related. Zhu and Sarkis (2004) caution, however, that failure to implement LSS programs carefully could inadvertently further degrade the environment, underscoring the need for a nuanced approach to LSS implementation in sustainability frameworks.

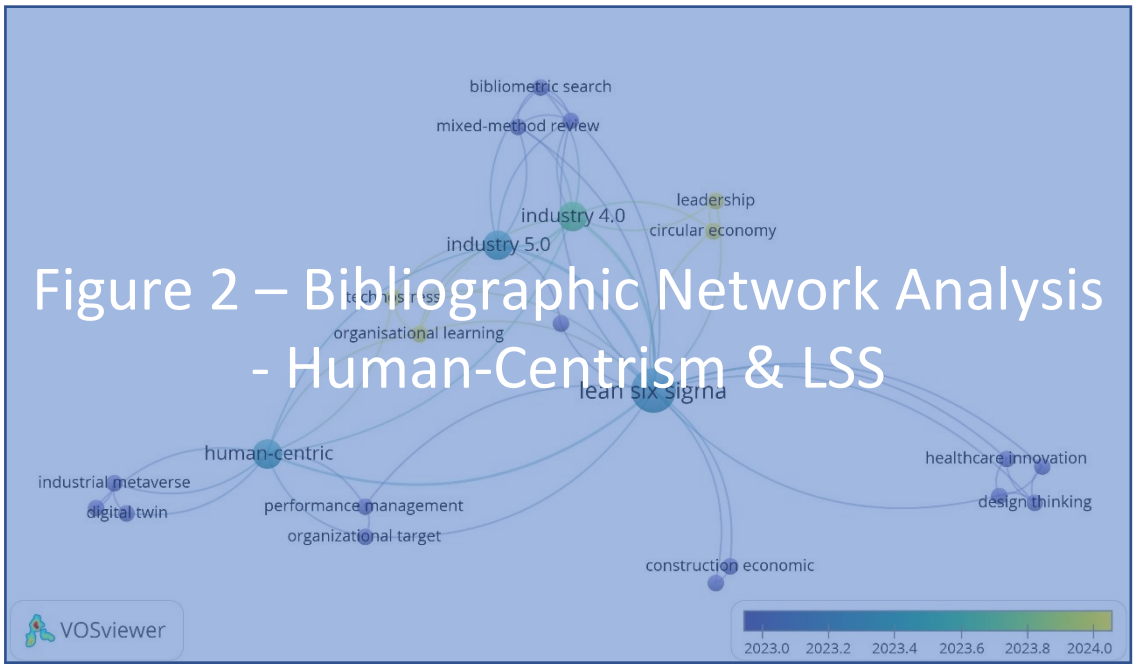
This analysis yielded preliminary results related to RQ5. These results will be presented in the results section.

Human-Centrism & LSS

The review identified a total of 78 articles that sought to understand the role of employee-centric approaches in the context of organisational improvement initiatives.

The BNA (Figure 2) revealed a linkage between human-centrism and LSS, with interconnected terms such as I5.0, Industry 4.0, circular economy, communication, design thinking, digital twin, fully mechanised, and leadership. We identified 58 links grouped into seven interconnected clusters. These clusters indicate a multidimensional approach to organisational improvement that stresses the importance of employee-centric practices. Finally, the research trend is shifting towards the concepts of technostress, organisational learning, circular economy, and leadership.

Figure 2 – Bibliographic Network Analysis - Human-Centrism & LSS



The results of the DSLR show that the most influential studies advance knowledge of LSS's impact on the human side of the organisation. Bortolotti *et al.* (2015) found that successful LSS companies placed stronger emphasis on soft practices, such as empowerment and teamwork, than on unsuccessful ones. Similarly, Achanga *et al.* (2006) identified critical

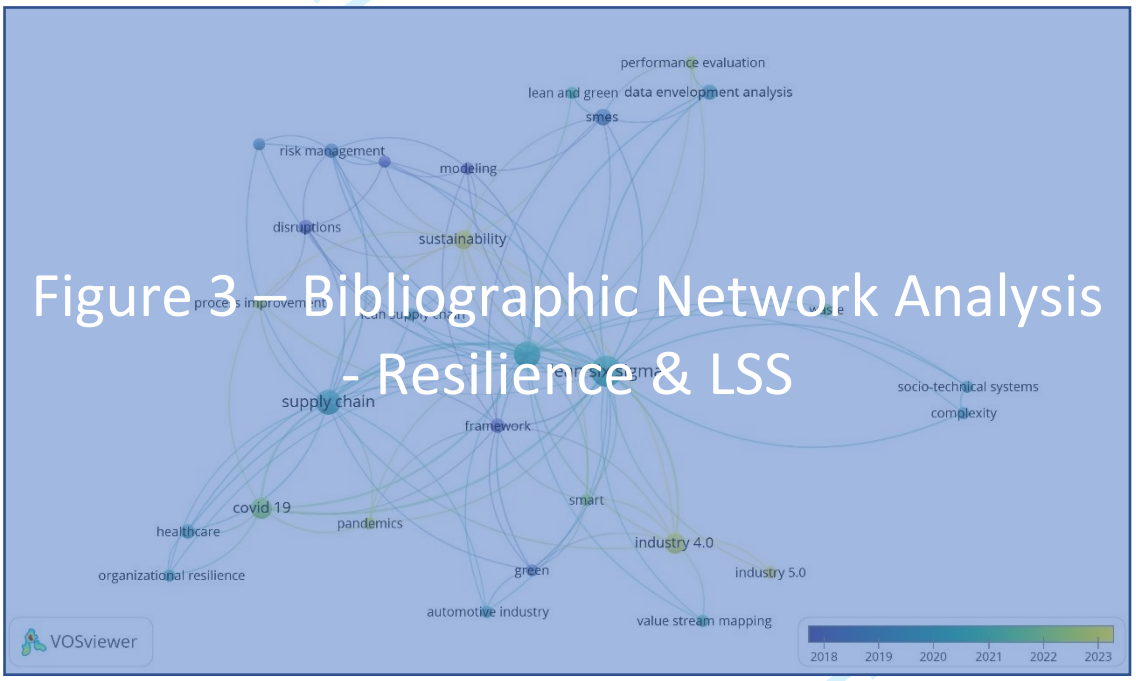
factors for successful LSS implementation, including leadership, organisational culture, and skills development. Birdi *et al.* (2008) and Forza (1996) highlighted the performance benefits derived from empowerment, training, and teamwork in LSS environments. Longoni *et al.* (2013) provided evidence that LSS adoption positively impacted health and safety performance, while Saurin and Ferreira (2009) reported improvements in workers' conditions following LSS implementation.

This analysis yielded the preliminary results to RQ6.

Resilience & LSS

The review identified a total of 83 articles analysing the relationship of LSS to organisational resilience. The BNA (Figure 3) revealed the connection of these two concepts to terms such as supply chain, Industry 4.0, sustainability, disruptions, framework, and risk management, with 103 links grouped into eight clusters.

Figure 3 – Bibliographic Network Analysis - Resilience & LSS



The analysis also indicated a research trend shifting towards concepts such as sustainability, Industry 4.0, process improvement, and performance evaluation. The discourse and research priorities are thus clearly evolving.

The DSLR shows that one of the most widely disseminated ideas is Birkie's (2016) emphasis on the role of LSS practices in leveraging agility to mitigate disruptions. Ruiz-Benítez *et al.* (2018) found that LSS serves as a driver of resilient practices. Lotfi and Saghiri (2018) demonstrated that greater resilience leads to better performance in delivery, cost, and time to recovery, while LSS positively affects cost, delivery, and flexibility. Similarly, Soliman *et al.* (2018) affirmed that LSS tends to increase resilience in complex socio-technical systems. De Sanctis *et al.* (2018) proposed a Lean Structural Network methodology, indicating that resilience enables quantification and prediction of

the local and global impacts of events. Resurreccion and Santos (2013) showed that LSS resilience-enhancement opportunities reduce expected economic loss. Finally, Praharsi *et al.* (2021) identified new ways to integrate LSS and resilience strategies and measures to maximise performance during pandemics.

This analysis provided the basis for the preliminary results to answer RQ7 and for a close relationship between LSS and resilience, with LSS practices supporting resilience across various dimensions. Significantly, no publications reported opposing results, reinforcing consensus on the positive impact of LSS on organisational resilience.

5. Experts' validation

As outlined in the methodology, we analysed and discussed the preliminary research findings (detailed in the previous section) with a panel of experts. These experts were asked to evaluate the accuracy of the findings and to provide recommendations for improvement.

The Experts' Validation helped identify potential gaps, inconsistencies, and shortcomings. An interview guide was developed from the findings derived from the previous analysis. It included four similarities, nine differences, and six ways in which LSS could support I5.0. After a series of previous contacts, the guide was shared with the experts via email and the confidentiality of the participants assured.

Overall, the feedback was constructive and affirming, reinforcing the accuracy of our results. The experts provided valuable insights and recommendations for refinement. For instance, one expert highlighted the differing concepts of value in LSS and I5.0.

As to future studies, some experts recommended the need for more in-depth research on specific areas. These areas included the financial investment needed for I5.0 adoption, development of an I5.0 assessment framework, identifying KPIs for I5.0, creating a roadmap for I5.0 implementation, integrating risk management into I5.0, exploring the specific application of each LSS tool in I5.0, and addressing the unresolved LSS paradox on the balance between efficiency and resilience and the dichotomy of exploitation versus innovation.

One expert even suggested that LSS could serve as the foundational of I5.0. Finally, experts recommended ways to enhance the clarity of specific concepts, such as the regulatory framework. All suggestions were evaluated, and recommendations pertinent to the scope of our study were integrated into the final research outcomes.

6. Results

Our analysis yielded valuable insights into the importance of integrating LSS into I5.0, demonstrating that the convergence of these paradigms has the potential to drive positive change across various societal and industrial domains. First, our research indicates no evidence of direct linkage between I5.0 and LSS in the current literature. A substantial corpus of 1794 published articles does, however, show connections between LSS and each pillar of I5.0. This body of research demonstrates an indirect but significant relationship, highlighting the potential for LSS to support the principles of I5.0 and thus helping to answer RQ1.

Second, several commonalities exist between LSS and I5.0. Both paradigms require specific organisational strategies and strong leadership to drive major changes (Zizic *et al.*, 2022). Both also aim to enhance efficiency and reduce waste to achieve sustainable outcomes

(Souza *et al.*, 2022), with the literature supporting the positive relationship between LSS and sustainability (Benkhati *et al.*, 2023). Further, both paradigms prioritise employee involvement, training, teamwork, and human-machine collaboration, which improve social performance and worker autonomy (Margherita and Zabudkina, 2023; Benkhati *et al.,* 2023). And both paradigms recognise the need for adaptability, although balancing LSS's efficiency with resilience can be challenging (Thakur-Weigold and Miroudot, 2024). Thus, in response to RQ2, we find many concepts shared by LSS and I5.0.

Third, RQ3 sought to identify the differences between and objectives of the different approaches. One key difference involved regulatory frameworks, as LSS aligns with existing regulations (Mollenkopf *et al.*, 2010), whereas I5.0 requires new frameworks (Rajesh, 2023). LSS and I5.0 also differ in strategic focus. LSS aims for business competitiveness (Palange and Dhatrak, 2021), while I5.0 prioritises human-centricity, sustainability, and societal well-being (Leng *et al.*, 2022). Implementation roadmaps vary, with LSS benefiting from established frameworks and I5.0 lacking a clear path (Leng *et al.*, 2022). Additionally, LSS has readily available assessment tools (Cabral *et al.*, 2012), whereas I5.0 lacks such methods and qualified personnel (Hassan *et al.*, 2024). The two paradigms also have different concepts of value. LSS focuses on shareholder value (Laureani *et al.*, 2010), whereas I5.0 spans profit, people, and society (Ivanov, 2022). Financial investment differs too, with LSS providing tangible benefits with lower investment (Yadav *et al.*, 2022) and I5.0 requiring extensive financial commitment for comprehensive transformation. As to complexity, LSS principles are straightforward (Elkhairi *et al.*, 2022), whereas I5.0 involves integrating advanced technology with its pillars (Leng *et al.*, 2022). Sustainability goals also differ, as LSS supports resource conservation (Boopathi, 2024) and I5.0 aims for broader environmental innovation (Baig and Yadegaridehkordi, 2024). The paradigms' human-centricity varies, with LSS focusing on employee development and organisational performance (Coetzee *et al.*, 2019), and I5.0 prioritising holistic human well-being (Leng *et al.*, 2022). Finally, the paradigms approach resilience differently. LSS is adaptable but does not focus inherently on unpredictable events (Thakur-Weigold and Miroudot, 2024), whereas I5.0 focuses on resilience (Leng *et al.*, 2023).

Fourth, LSS can promote I5.0 through its well-established, structured methodology, which can be adapted to align with I5.0's goals (Badhotiya *et al.*, 2024; Peças *et al.*, 2022), as suggested in RQ4. LSS fosters a continuous improvement culture, which aligns with the dynamic nature of I5.0, promoting an environment that embraces adaptation, learning, and ongoing enhancements (Costa *et al.*, 2019). LSS's focus on risk management prepares I5.0 initiatives to handle uncertainties (Zaporowska and Szczepański, 2024), and LSS's error learning from past failures provides valuable insights to anticipate challenges (Sony *et al.*, 2019). Human-machine collaboration in LSS aligns with I5.0's human-oriented discipline, achieving a harmonious blend of humane processes and result-driven environments (Rahardjo *et al.*, 2023). Finally, LSS's comprehensive training programs ensure workforce proficiency and effective contribution to overarching objectives (Skalli *et al.*, 2024).

Fifth, LSS extends its applications through the triple-bottom-line of social, economic, and environmental dimensions (Batwara *et al.*, 2024), and research confirms that LSS is positively related to all dimensions of the triple-bottom-line (Wadood *et al.*, 2023). LSS identifies and eliminates waste in production processes, conserving resources, minimising environmental impact, and reducing energy consumption (Ahmed *et al.*, 2021). It also aims to reduce rework, scrap, and pollution costs and synthesise economic and ecological quantification of various cases (Rüdele *et al.*, 2024). It helps to conserve energy and optimise production processes, lowering resource consumption and environmental impact. Srinivasan *et al.* (2024) reported these results and noted improvements in overall

process efficiency and lead time reduction. The common philosophy and goals shared by LSS and sustainable operations make it easier for LSS-first companies to implement sustainability practices (Piercy and Rich, 2015). External pressures, including public environmental awareness and regulatory demands, drive firms to implement LSS for improved environmental performance (Cherrafi *et al.*, 2016). LSS then enhances sustainability within I5.0 (RQ5).

Sixth, LSS enhances human-centricity by recognising workers as thinkers, fostering self-esteem, confidence, and satisfaction with work (Klein *et al.*, 2023). These findings help to answer RQ6. LSS reduces manual and repetitive tasks, improving workplace ergonomics and safety (Pereira *et al.*, 2023). LSS companies prioritise employee engagement and development, as seen in Kaizen events that promote continuous improvement and teamwork that consider employees' perspectives (Costa *et al.*, 2019). LSS also empowers workers to participate in decision-making. The resulting increase in productivity and decrease in customer complaints positively influences employee well-being and organisational performance (Naeemah and Wong, 2023).

Seventh, academia provides strong evidence for the relationship between LSS and resilience (RQ7). LSS enhances decision-making processes, enabling organisations to respond adeptly to market changes and challenges and thus increasing resilience (Ince *et al.*, 2023). It also increases customer satisfaction and loyalty, fostering a solid customer base that enhances organisational resilience against competitors (Huo *et al.*, 2024). LSS improves social performance and systematic problem-solving, equipping organisations to address challenges and find solutions and enhancing resilience (Frank *et al.*, 2024). Additionally, LSS streamlines supply chain processes, enabling organisations to respond quickly to customer demands and market needs, enhancing resilience in the face of uncertainties (Zarbakhshnia and Karimi, 2024).

Having answered all research questions, we will discuss the results in the following section.

7. Discussion and contribution

The current industrial landscape demands transformative change to address pressing human and environmental concerns (Doyle-Kent and Kopacek, 2020). While I5.0 is in its early stages, its focus on sustainability, human-centricity, and resilience aligns with these critical needs (Paschek *et al.*, 2022). The paradigm can benefit from LSS's well-established methodology for performance improvement in manufacturing. LSS's proven effectiveness over decades positions it as a powerful tool for challenging and optimising production practices (Patel *et al.*, 2022).

As proposed in RQ4, our study indicates the significant promise of integrating LSS principles into I5.0 implementation. Such integration can foster inclusive growth, empower workers, and create resilient manufacturing ecosystems capable of withstanding unforeseen disruptions (RQ2). LSS and I5.0 do differ in some respects: regulatory framework, strategic focus, implementation roadmaps, concepts of value, financial investment, sustainability goals, human-centricity, and resilience (RQ3). Despite these differences, I5.0 stands to gain considerably from LSS's structured approach and positive results proven over decades, as LSS enhances sustainability (RQ5), fosters human-centricity (RQ6), and strengthens organisational resilience (RQ7).

Contribution to theory

As I5.0 is a nascent paradigm in its early stages, our study significantly enriches the body of academic knowledge on the next phase of industrial evolution through its systematic analysis of the convergence of LSS and I5.0. This analysis builds on previous studies, which have analysed issues such as the integration of LSS with Industry 4.0 within the I5.0 framework (Moraes *et al.*, 2023), the connection between LSS and I5.0's human-centric focus (Rahardjo *et al.*, 2023), the relationship between I5.0 and TQM (Chaabi, 2022), and the links between LSS and Industry 4.0 (Ejsmont *et al.*, 2020). These findings encourage comparative analyses of LSS and other continuous improvement methodologies in the context of I5.0.

Our study posits that integrating LSS principles into the I5.0 paradigm can catalyse organisational transformation, fostering sustainability, human-centricity, and resilience amid evolving socioeconomic challenges. It contributes to the development of theoretical support for the convergence of LSS and I5.0 and provides a framework for further research in this emerging field.

The study results stress the need for interdisciplinary collaboration among researchers from various fields to fully understand the complex relationship between LSS and I5.0. Our findings thus open new avenues for academics to explore and from which to develop innovative research questions and methodologies. The key research gaps and unexplored avenues for future investigation identified also lay the groundwork for scholars to deepen their understanding of this dynamic relationship.

Contribution to practice

The study findings have significant implications for policymakers, researchers, educational institutions, and industry practitioners. Policymakers are urged to shape proactively the regulatory frameworks that facilitate convergence of LSS and I5.0 to promote innovation, sustainability, and social responsibility. Researchers are encouraged to explore interdisciplinary approaches and collaborative initiatives to advance theoretical understanding and practical applications of LSS in the I5.0 context. Educational institutions should adapt their programs to transfer both theoretical knowledge and practical skills effectively. We call on industry practitioners to embrace a culture of continuous improvement, invest in workforce development, and adopt strategies to navigate complexities effectively.

This study complements practical articles that focus on transitioning from LSS and Industry 4.0 to I5.0 (Eriksson *et al.*, 2024) and frameworks for integrating LSS with Industry 4.0 (Skalli *et al.*, 2024). It also provides actionable insights for organisations navigating the complexities of I5.0 implementation and seeking to leverage the synergies of LSS.

By explaining the potential benefits and challenges associated with integrating LSS into I5.0, the study equips practitioners with knowledge and foresight needed to make informed strategic decisions to achieve operational excellence and competitive advantage. The results identify the strategic benefits of integrating LSS into I5.0 implementation, giving practitioners a roadmap for leveraging LSS's structured approach to optimise processes within the I5.0 framework. Such optimisation leads to increased efficiency, cost-savings, and improved product quality.

Understanding the potential challenges also enables practitioners to plan mitigation strategies, ensuring a smooth transition to I5.0. The findings stress the importance of workforce development in the context of LSS and I5.0, as such development enables practitioners to design training programs that give employees the necessary skills to operate effectively within this “converged” environment. These skills must include both

technical skills related to I5.0 technologies and soft skills such as critical thinking, problem-solving, and collaboration, which are essential for continuous improvement under LSS principles.

8. Conclusion, limitations, and future research

The emergence of I5.0 as a focus of research and innovation has sparked significant interest and speculation in academic and industrial communities. We propose that LSS methodology is a valuable tool for implementing and enhancing I5.0. With its proven track record in enhancing operational excellence and driving organisational success, LSS can contribute significantly to realising the goals of I5.0. The results of this study, which were validated by a panel of experts, pioneer in the attempt to synthesise the extensive existing knowledge on LSS and I5.0, providing valuable insights into these paradigms' theoretical underpinnings, practical implications, and future trajectories.

Limitations

Despite its valuable insights, this study has limitations. The nascent state of I5.0 research poses challenges for practical implementation and empirical validation, necessitating further interdisciplinary collaboration and empirical research. As the number of experts in LSS and I5.0 grows, validation by a broader, more diverse pool of experts would provide additional perspectives and insights, enriching the study's findings and recommendations. Future studies should address these limitations to enhance the robustness and applicability of the research outcomes.

Scope of future research

The emergence of I5.0 introduces new ideas, concepts, and technologies into the debate over the future of manufacturing and logistics (Ivanov, 2022). Our study proposes an agenda for future research based on the gaps and insufficiencies detected, unanswered or insufficiently answered questions in the current literature, and issues on which research should focus to fill these gaps (Buer *et al.*, 2018). Given the high stakes, it is crucial that future research advance holistic understanding of the conjunction between LSS and the pillars of I5.0 (Souza *et al.*, 2022).

Research efforts should concentrate on identifying the most effective strategies for merging LSS and I5.0 to maximise their synergistic potential. Developing a roadmap for implementing LSS principles in the context of I5.0 is essential. Such a roadmap should be tailored to the characteristics of individual organisations and address potential obstacles to effective implementation, ultimately guiding organisations' seamless transition to integrated LSS and I5.0 practices. Defining the roles of various stakeholders (including society, managers, policymakers, and members of the public sector) is crucial for fostering, controlling, and enhancing adoption of the new paradigm. Further, understanding stakeholders' perspectives and engaging them in the implementation process is essential to promoting collaboration and ensuring the success of I5.0 initiatives.

In sum, this study lays the groundwork for future research on the complex relationship between LSS and I5.0. Academics, practitioners, and policymakers can build on this foundation to better understand and navigate the complexities of LSS-I5.0 integration and thus to advance toward a future of sustainability, human well-being, and resilience.

Collaboration, adaptability, and commitment to excellence are essential as organisations transform themselves to achieve the I5.0 paradigm, which leverages technology as a catalyst for positive societal change and environmental preservation.

We conclude with Anatan's (2020) assertion that I5.0 represents the most complete vision of and a positive attitude towards the future. The goal is for I5.0 to emerge as a transformative force for positive social change, generating a future of socioeconomic prosperity and sustainability. As LSS is one of the best options to support this transformation, we could call this blend LSS5.0. LSS5.0 promises to create a future where innovation thrives, businesses flourish, society prospers, and the planet is preserved.

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Table I - Research protocol flowchart

Input

Research databases	World of Science Core Collection (WoSCC), Scopus, Emerald, Science Direct, EBSCOhost, and ProQuest
Publication type	Peer-reviewed article OR Early access
Language	Only papers in English
Search period	2020 - March 2024
Search field	Title, keywords, or abstract
Search terms	”industry 5.0” OR ”ind5.0” OR ”ind.5.0” OR ”I5.0”
	”lean six sigma” OR ”lean production” OR ”lean manufacturing” OR ”lean management” OR ”lean philosophy” OR ”six sigma”
	sustain*
	"huma*-c*" OR "huma* c*" OR "huma* robo*" OR "human-robo*" OR "cobot*"
	resilie*
Criteria for inclusion	Articles that refer exclusively to I5.0 & LSS
Criteria for exclusion	Articles that use I5.0 or LSS as a supportive concept only

Software	VOSviewer version 1.6.18
Type of analysis	Co-occurrence and author keywords

Research databases	WoSCC and Scopus
Most influencial articles	15 most-cited articles per pillar (45 in total)
LSS & I5.0 link	All published articles except for LSS & Sustainability, for which we used the 60 latest articles

Sector	Professionals, consultants, and academia
System	Email and videoconference interviews

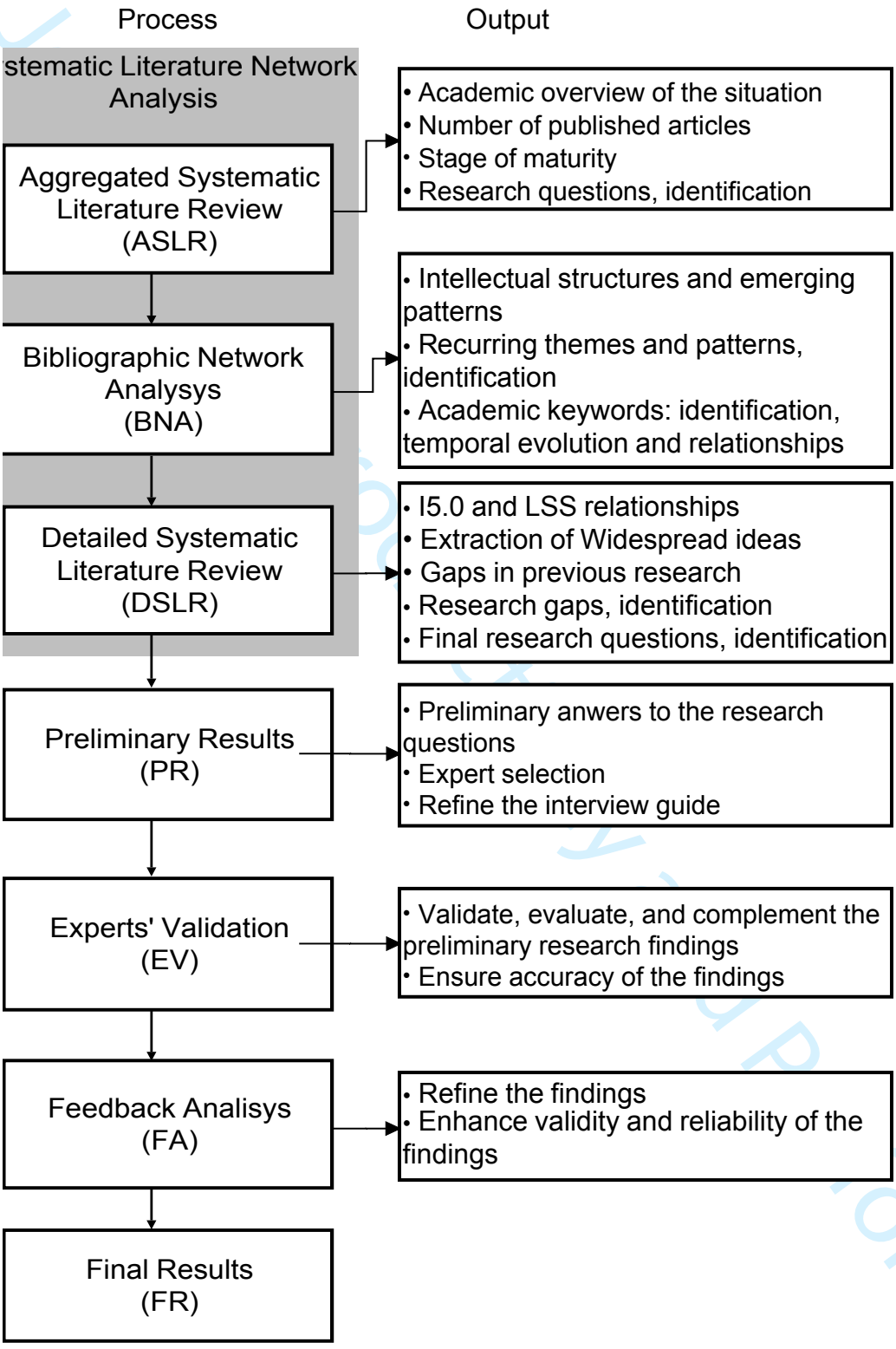
Process
Output
stematic Literature Network Analysis
Aggregated Systematic Literature Review (ASLR)
Bibliographic Network Analysys (BNA)
Detailed Systematic Literature Review (DSLR)
Preliminary Results (PR)
Experts' Validation (EV)
Feedback Analisys (FA)
Final Results (FR)
• Academic overview of the situation
• Number of published articles
• Stage of maturity
• Research questions, identification
• Intellectual structures and emerging patterns
• Recurring themes and patterns, identification
• Academic keywords: identification, temporal evolution and relationships
• I5.0 and LSS relationships
• Extraction of Widespread ideas
• Gaps in previous research
• Research gaps, identification
• Final research questions, identification
• Preliminary anwers to the research questions
• Expert selection
• Refine the interview guide
• Validate, evaluate, and complement the preliminary research findings
• Ensure accuracy of the findings
• Refine the findings
• Enhance validity and reliability of the findings

Table II - Number of articles

	WoS	Scopus	Emerald	ScienceDirect
Industry 5.0	652	744	307	240
LSS	8192	9673	465	1849
LSS & Industry 5.0	9	12	1	1
LSS & Sustainable	1009	1445	110	276
LSS & Human-Centric	46	66	20	11
LSS & Resilient	71	63	14	23

EBSCOhost	ProQuest
303	356
4322	6868
1	3
553	651
19	8
30	39

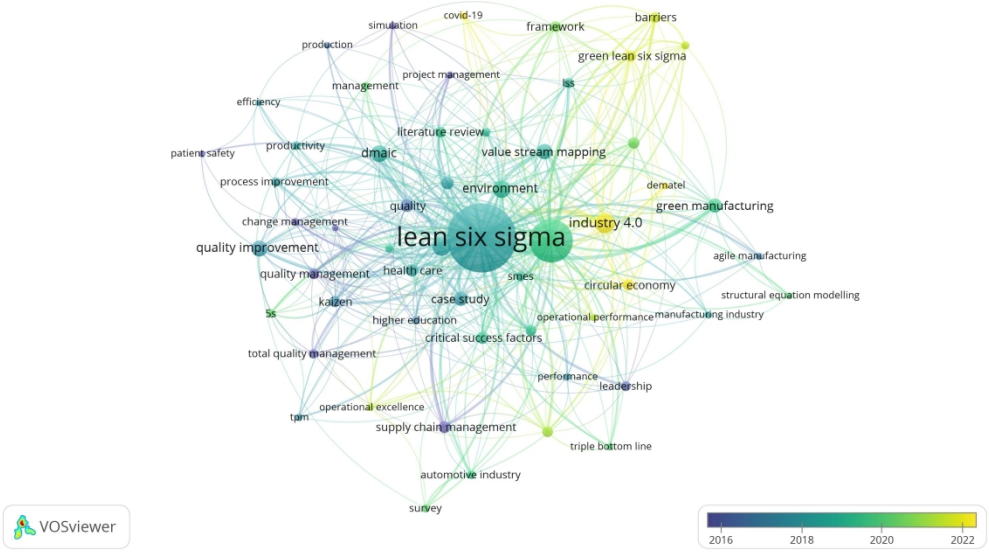

Figure 1 – Bibliographic Network Analysis - Sustainability & LSS

1059x625mm (72 x 72 DPI)

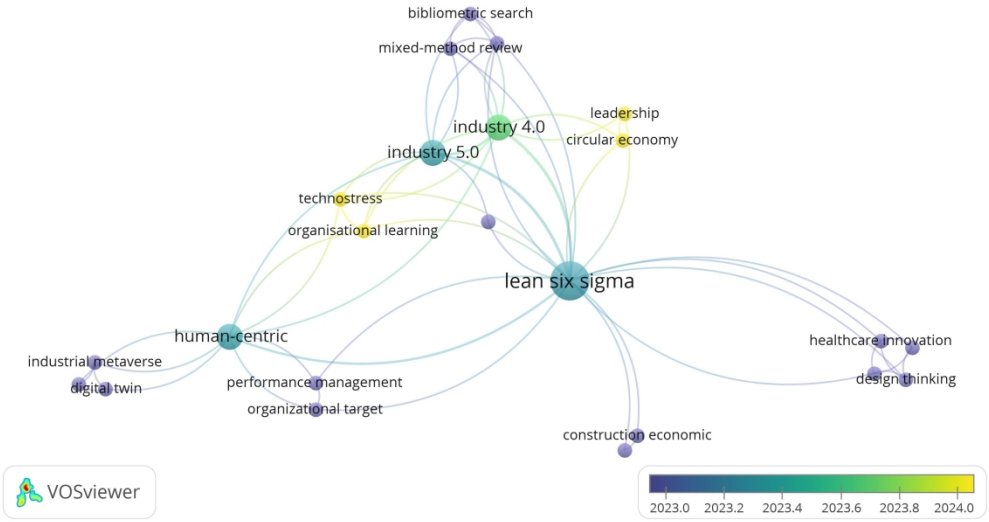

Figure 2 – Bibliographic Network Analysis - Human-Centrism & LSS

1059x625mm (72 x 72 DPI)

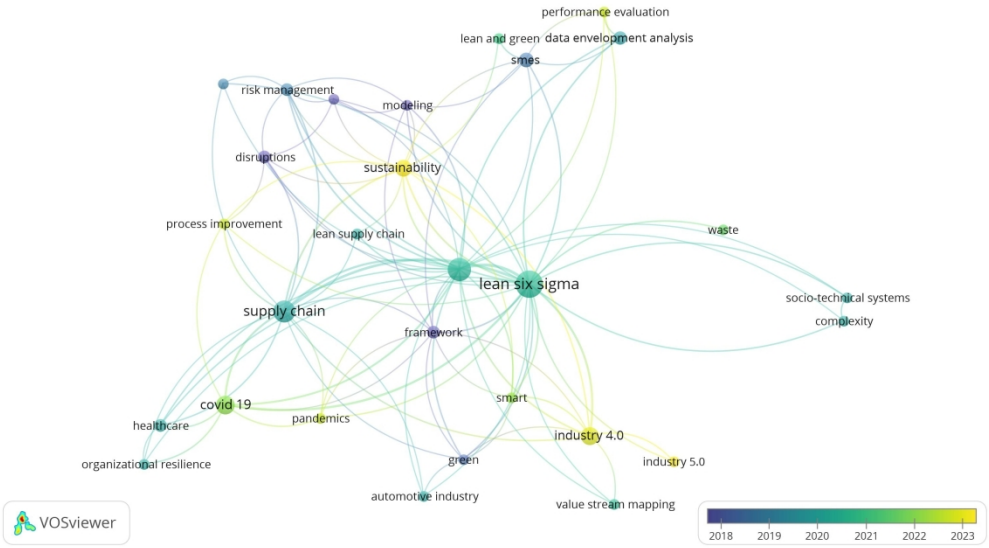

Figure 3 – Bibliographic Network Analysis - Resilience & LSS

1059x625mm (72 x 72 DPI)