Programa de Doctorado en Ciencias Sociales y Jurídicas

Industria 5.0: Hacia una Industria Sostenible, Humano-Centrista y Resiliente - Sinergias con Lean Six Sigma

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A mis padres, Carmen y Luis.

A mis hijos, Andrea y Álex.

A mi director y codirector de esta tesis.

Y a las innumerables personas que con infinita paciencia me han apoyado en este transformador viaje.

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PUBLICACIONES

La presente Tesis Doctoral, titulada "Industria 5.0: Hacia una Industria Sostenible, Humano-Centrista y Resiliente - Sinergias con Lean Six Sigma", se presenta bajo la modalidad de tesis por compendio de las siguientes publicaciones:

- Cuevas, C., Mira-Solves, I. and Verdu-Jover, A. (2024), "Industry 5.0's pillars and Lean Six Sigma: mapping the current interrelationship and future research directions", *International Journal of Productivity and Performance Management*, Emerald Publishing, Vol. 74 No. 4, pp. 1347–1364, doi: 10.1108/IJPPM-08-2023-0404/FULL/XML.

  https://www.emerald.com/insight/content/doi/10.1108/ijppm-08-2023-0404/full/html

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- Cuevas-Lopez-de-Baro, C., Mira-Solves, I. and Verdú-Jover, A. (2025), "Assessment model for Industry 5.0: A holistic approach to readiness and integration", *Journal of Industrial Information Integration*, Elsevier, Vol. 46, p. 100855, doi: 10.1016/J.JII.2025.100855.

  https://www.sciencedirect.com/science/article/pii/S2452414X25000792?via%3Dihub

  Indicios de Calidad: SJR 2024: 2.445 Q1, H-Index 62 (Industrial and Manufacturing Engineering).

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1.1. Otras publicaciones que forman parte de la tesis doctoral

Los dos artículos anteriores se complementan con el siguiente artículo que se encuentra **en proceso de evaluación**:

- Cuevas-Lopez-de-Baro, C., Mira-Solves, I. and Verdú-Jover, A., "Barriers to Industry 5.0 adoption and perception-based differences between Lean and non-Lean Six Sigma firms". *IEEE Transactions on Engineering Management*.

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RESUMEN

Las organizaciones se enfrentan al desafío transformacional de adaptarse a un entorno caracterizado por una disrupción tecnológica acelerada, crecientes demandas de sostenibilidad y nuevas expectativas sociales, sin comprometer su cometido como generadoras de prosperidad (Awad and Martín-Rojas, 2024). Esta transformación está impulsada por múltiples factores disruptivos como la aceleración tecnológica, las crecientes demandas sociales, la presión por alcanzar los Objetivos de Desarrollo Sostenible, y la necesidad de modelos productivos más adaptativos, éticos y sostenibles.

Frente a este escenario, emergen dos interrogantes fundamentales: ¿hacia qué modelo deben evolucionar las organizaciones? y ¿cómo hacer viable esta transformación?. Como respuesta a la primera pregunta, la Industria 5.0 (I5.0) emerge como un paradigma industrial que reconfigura el actual modelo productivo al complementar —y en parte corregir— el enfoque tecno-céntrico de la Industria 4.0 (Maddikunta *et al.*, 2022), centrado en maximizar beneficios a través de la eficiencia digital, la automatización avanzada y la conectividad de sistemas ciberfísicos (Zizic *et al.*, 2022).

Este nuevo paradigma está articulado en torno a tres pilares: la sostenibilidad, que impulsa una gestión responsable de los recursos naturales y la minimización del impacto ambiental; el humano-centrismo, que sitúa al trabajador en el núcleo del sistema productivo, promoviendo su desarrollo, bienestar y participación activa; y la resiliencia organizativa, entendida como la capacidad de anticipar, absorber y adaptarse ante disrupciones, garantizando la continuidad operativa en entornos inciertos. Esta evolución pretende no solo mantener la competitividad y el retorno a los accionistas, sino también garantizar la armonía entre el progreso tecnológico, la justicia social, el bienestar laboral y la responsabilidad ambiental (Breque *et al.*, 2021). En definitiva, la I5.0 redefine el propósito de la industria del futuro, orientándola hacia una prosperidad compartida que responda simultáneamente a los desafíos económicos, humanos y ecológicos de la nueva era.

En respuesta al segundo interrogante, la metodología Lean Six Sigma (LSS) emerge como un catalizador potencial para esta transición. Con más de tres décadas de validación empírica, LSS se ha consolidado como un enfoque robusto y sistemático de mejora continua, ampliamente reconocido por su eficacia en la optimización de procesos, la reducción de la variabilidad, el aseguramiento de la calidad y el incremento de la eficiencia operativa en diversos contextos industriales y de servicios (Raja Sreedharan and Raju, 2016). Su aplicación ha demostrado generar importantes beneficios tanto en términos de productividad como de satisfacción del cliente y retorno económico, consolidándose como una herramienta clave para la excelencia operacional (Antony *et al.*, 2023). Esta metodología puede ser una posible respuesta a la segunda pregunta.

Sin embargo, a pesar de su madurez metodológica y su amplia adopción, la posible convergencia entre LSS y los principios fundamentales de la I5.0 (sostenibilidad, humano-centrismo y resiliencia) representa un campo de investigación incipiente y escasamente explorado. Hasta la fecha, la literatura científica carece de marcos conceptuales sólidos y guías operativas que faciliten la integración efectiva de ambos enfoques. Esta ausencia de modelos integradores limita la capacidad de las organizaciones para aprovechar el potencial sinérgico entre la estructura metodológica de LSS y la visión transformadora que propone la I5.0. Por tanto, se hace necesario avanzar en investigaciones que permitan explorar, conceptualizar y validar esta interacción, con el fin de construir una transición estructurada y eficiente hacia el nuevo paradigma industrial. En este contexto, la I5.0 surge para vincular a quienes creen en el poder de las personas para crear innovaciones y a quienes conectan las innovaciones con nuevas ideas para resolver problemas complejos de la economía global (Anatan, 2020).

El objetivo general de esta tesis doctoral ha sido doble: por un lado, generar conocimiento teórico, metodológico y aplicado que facilite la adopción efectiva de la I5.0 en las organizaciones; y por otro, analizar el potencial del LSS como palanca estratégica para apoyar dicha transición. La investigación se ha estructurado en modalidad de compendio de publicaciones, integrando tres estudios complementarios que abordan progresivamente elementos clave de la I5.0 y su implantación exitosa en las empresas.

El primer artículo identifica las convergencias entre los pilares de la I5.0 y las prácticas de LSS. Los resultados posicionan a esta última como una metodología alineada y potencialmente útil para facilitar la transición hacia la I5.0. El segundo desarrolla y valida un modelo integral para evaluar la preparación organizacional hacia la I5.0. Este modelo ofrece a las organizaciones una herramienta diagnóstica que les permite identificar su nivel de madurez y definir sus planes estratégicos. Finalmente, el tercero identifica las principales barreras que dificultan la implementación de la I5.0, y analiza herramientas específicas de LSS que pueden emplearse para mitigar dichas barreras.

En conjunto, la tesis aporta una contribución teórica al integrar dos marcos hasta ahora poco conectados, una herramienta práctica validada que facilita la toma de decisiones en contextos organizativos, y proporciona evidencia empírica sobre el papel diferencial que puede desempeñar LSS en la superación de obstáculos asociados a la transformación industrial. Además, los resultados de la tesis muestran que LSS no solo mantiene su relevancia en la era posdigital, sino que puede actuar como un catalizador metodológico esencial para guiar a las organizaciones en su transición efectiva hacia la Industria 5.0.

Con todo, esta tesis contribuye a configurar una línea de investigación que aporta nuevo conocimiento científico y que responde a los retos económicos, humanos y ecológicos del tejido empresarial global, y más concretamente, a algunas de las políticas prioritarias de la Unión Europea como The European Green Deal (Fetting, 2020), An Economy that Works for People (European Commission, 2020a) y A Europe Fit for the Digital Age (European Commission, 2020b), con las que está totalmente alineada y las fortalece.

ABSTRACT

Organizations face the transformational challenge of adapting to an environment characterized by accelerated technological disruption, growing sustainability demands, and new social expectations, without compromising their role as generators of prosperity (Awad and Martín-Rojas, 2024). This transformation is driven by multiple disruptive factors such as technological acceleration, growing social demands, the pressure to achieve the Sustainable Development Goals, and the need for more adaptive, ethical, and sustainable production models.

Faced with this scenario, two fundamental questions emerge: What model should organizations evolve toward? And how can this transformation be made viable? In response to the first question, Industry 5.0 (I5.0) emerges as an industrial paradigm that reconfigures the current production model to complement—and in part correct—the techno-centric approach of Industry 4.0 (Maddikunta et al., 2022), which focuses on maximizing profits through digital efficiency, advanced automation, and the connectivity of cyber-physical systems (Zizic et al., 2022).

This new paradigm is articulated around three pillars: sustainability, which promotes responsible management of natural resources and the minimization of environmental impact; human-centrism, which places the worker at the core of the production system, promoting their development, well-being, and active participation; and organizational resilience, understood as the ability to anticipate, absorb, and adapt to disruptions, ensuring operational continuity in uncertain environments. This evolution aims not only to maintain competitiveness and shareholder returns, but also to ensure harmony between technological progress, social justice, employee well-being, and environmental responsibility (Breque et al., 2021). Ultimately, I5.0 redefines the purpose of the industry of the future, orienting it toward shared prosperity that simultaneously responds to the economic, human, and ecological challenges of the new era.

In response to the second question, the Lean Six Sigma (LSS) methodology emerges as a potential catalyst for this transition. With more than three decades of empirical validation, LSS has established itself as a robust and systematic approach to continuous improvement, widely recognized for its effectiveness in optimizing processes, reducing variability, ensuring quality, and increasing operational efficiency in various industrial and service contexts (Raja Sreedharan and Raju, 2016). Its application has been shown to generate significant benefits in terms of productivity, customer satisfaction, and economic returns, establishing itself as a key tool for operational excellence (Antony et al., 2023). Thus, this methodology may provide an answer to the second question.

However, despite its methodological maturity and widespread adoption, the potential convergence between LSS and the principles of I5.0 (sustainability, human-centrism, and resilience) represent a nascent and underexplored field of research. To date, the scientific literature lacks solid conceptual frameworks and operational guides that facilitate the effective integration of both approaches. This absence of integrative models limits organizations' ability to leverage the synergistic potential between the LSS methodological framework and the transformative vision proposed by I5.0. Therefore, it is necessary to advance research that explores, conceptualizes, and validates this interaction in order to enable a structured and efficient transition toward the new industrial paradigm. In this context, I5.0 emerges to connect those who believe in the power of people to create innovations and those who connect innovations with new ideas to solve complex problems in the global economy (Anatan, 2020).

The overall objective of this doctoral thesis was twofold: first, to generate theoretical, methodological, and applied knowledge that facilitates the effective adoption of I5.0 in organizations; and second, to analyze the potential of LSS as a strategic lever to support this transition. The research has been structured as a compendium of publications, integrating three complementary studies that progressively address key elements of I5.0 and its successful implementation in companies.

The first article identifies the convergences between the pillars of I5.0 and LSS practices. The results position the latter as an aligned and potentially useful methodology for facilitating the transition to I5.0. The second article develops and validates a comprehensive model for assessing organizational readiness for I5.0. This model offers organizations a diagnostic tool that enables them to identify their maturity level and define their strategic plans. Finally, the third article identifies the main barriers to I5.0 implementation and analyzes specific LSS tools that can be used to mitigate these barriers.

Overall, the thesis makes a theoretical contribution by integrating two previously poorly connected frameworks, provides a validated practical tool that facilitates decision-making in organizational contexts, and offers empirical evidence on the differential role that LSS can play in overcoming obstacles associated with industrial transformation. Furthermore, the results of the thesis show that LSS not only maintains its relevance in the post-digital era but can also act as an essential methodological catalyst to guide organizations in their effective transition to Industry 5.0.

In summary, this thesis contributes to a line of research that provides new scientific knowledge and responds to the economic, human, and ecological challenges facing the global business community, and more specifically, to some of the European Union's priority policies, such as the European Green Deal (Fetting, 2020), An Economy that Works for People (European Commission, 2020a), and A Europe Fit for the Digital Age (European Commission, 2020b), with which it is fully aligned and which it strengthens.

1. INTRODUCCIÓN

La evolución histórica de las revoluciones industriales ha estado marcada por hitos tecnológicos que redefinieron la producción, la estructura económica y la sociedad. La Industria 1.0 introdujo la mecanización mediante el uso del vapor; la Industria 2.0 incorporó la electricidad y la producción en masa; la Industria 3.0 transformó la sociedad a través de la automatización y el auge de las tecnologías de la información; y la actual Industria 4.0 ha consolidado la digitalización mediante la interconexión entre el mundo físico y virtual (Leng *et al.*, 2022).

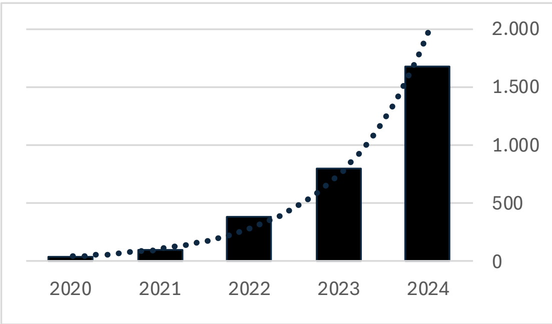
La I5.0, en este contexto evolutivo, representa un salto cualitativo respecto a sus predecesoras. Construida sobre la base tecnológica de la Industria 4.0, propone una transformación profunda del paradigma industrial, reorientando su propósito hacia una producción más sostenible, centrada en el ser humano y resiliente (Breque *et al.*, 2021). A diferencia de la Industria 4.0, cuyo énfasis principal está centrado en la eficiencia y la maximización del beneficio empresarial (Zizic *et al.*, 2022), la I5.0 surge como una respuesta a sus limitaciones éticas, sociales y medioambientales, proponiendo una visión equilibrada que promueve una relación armónica con el entorno natural, entornos laborales inclusivos y organizaciones adaptativas.

El concepto de sostenibilidad en la I5.0 implica una gestión responsable de los recursos, con énfasis en la reducción del impacto ambiental y la eficiencia ecológica. El pilar humano-céntrico aboga por entornos laborales más seguros, saludables, diversos y empoderadores, en los que las personas no sean desplazadas por la tecnología, sino potenciadas por ella. Por su parte, la resiliencia se refiere a la capacidad organizacional para anticiparse, adaptarse y recuperarse frente a disrupciones, crisis o cambios inesperados en el entorno (Breque *et al.*, 2021).

El creciente interés académico por este nuevo paradigma puede observarse en el aumento exponencial de publicaciones científicas indexadas (Figura 2), lo que refleja su consolidación como una línea de investigación emergente.

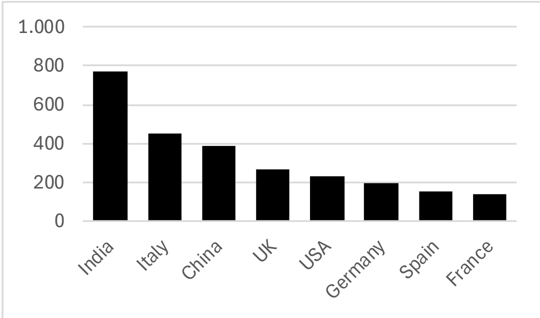
Asimismo, el análisis por países (Figura 3) muestra que la I5.0 constituye un fenómeno global, con India, Italia, China, Reino Unido y Estados Unidos como principales polos de producción científica.

Figura 2: Evolución temporal



(Fuente: Elaboración propia con datos de Scopus)

Figura 3: Publicaciones por países



(Fuente: Elaboración propia con datos de Scopus)

En el caso de Europa, la I5.0 ha sido adoptada por la Comisión Europea desde 2022 dentro de su visión estratégica de futuro para configurar el futuro tejido industrial, integrándose en las directrices del Directorate-General for Research and Innovation.

En este escenario de transformación profunda, el Lean Six Sigma (LSS) se presenta como una metodología madura y consolidada para la mejora continua, con un amplio historial de aplicación en la optimización de procesos, el aseguramiento de la calidad y la eficiencia operativa en contextos industriales diversos (Elkhairi *et al.*, 2022). Su aplicabilidad ha sido validada empíricamente durante más de tres décadas (Pepper and Spedding, 2010) y se estima que aproximadamente un 70 % de los fabricantes a nivel mundial integran prácticas LSS en sus operaciones (Adams, 2021).

Este trabajo de investigación se ubica en la intersección entre la I5.0 y el LSS, con una orientación alineada con el modelo de la quinta hélice -industria, gobierno, academia, ciudadanía y medioambiente- (Carayannis *et al.*, 2022) como base para la generación de valor compartido. En un contexto marcado por la automatización acelerada, las crisis medioambientales y la creciente demanda de modelos industriales éticos, sostenibles y adaptativos, esta tesis responde a la necesidad de comprender en profundidad el paradigma de la I5.0 y explorar cómo una metodología robusta como LSS puede actuar como facilitador de su implementación efectiva.

El objetivo general de la investigación es contribuir a la comprensión, evaluación y adopción del paradigma de la I5.0 en entornos organizativos. Este propósito se desglosa en tres objetivos específicos, abordados respectivamente en los artículos que conforman el compendio: (i) explorar las posibles interrelaciones teóricas y prácticas entre I5.0 y LSS, con el fin de determinar si esta última puede actuar como catalizador del nuevo paradigma industrial; (ii) desarrollar un modelo de evaluación integral que permita diagnosticar el nivel de preparación organizacional para adoptar la I5.0; y (iii) identificar y priorizar las principales barreras para su implementación, proponiendo herramientas específicas de LSS para su mitigación.

En coherencia con estos objetivos, la tesis se vertebra en torno a una pregunta de investigación general: ¿Cómo pueden las organizaciones abordar de manera efectiva la transición e implementación de la I5.0? Esta cuestión se despliega en una serie de preguntas específicas que orientan cada uno de los artículos.

En el primer artículo, se analiza el grado de alineación entre los principios de la I5.0 y el LSS, en base a las preguntas: ¿cuál es el grado de alineación entre los principios de la I5.0 y el LSS? y ¿puede el LSS contribuir que los pilares de la I5.0 sean una realidad? Estas cuestiones permiten establecer los puntos de convergencia y divergencia entre la I5.0 y el LSS, así como establecer el marco de compatibilidad entre ambos marcos.

El segundo artículo aborda el diseño de una herramienta diagnóstica específica, planteando la pregunta ¿cómo puede evaluarse de forma integral la preparación de una organización para adoptar la I5.0?

Finalmente, en el tercer trabajo se exploran los obstáculos prácticos de la implementación y se sugieren estrategias para superarlos, respondiendo a las preguntas: ¿cuáles son las principales barreras para la implementación de la I5.0?, ¿cómo varían estas barreras según el contexto organizacional -particularmente entre empresas LSS y no LSS-?, y ¿qué herramientas de LSS son útiles para superar esas barreras?.

Estas preguntas no sólo delimitan el alcance de la investigación de cada artículo, sino que, en conjunto, configuran un eje vertebrador coherente para toda la tesis, permitiendo una exploración integrada de la I5.0 desde una perspectiva conceptual, metodológica y aplicada.

La estructura general de la tesis se organiza en torno a estos tres trabajos que, si bien pueden ser tratados de forma independiente, han sido diseñados para construir una línea de investigación que avanza desde la fundamentación conceptual hasta la propuesta de soluciones prácticas. Esta secuencia no es meramente formal, sino que responde a una lógica investigativa que sitúa a la I5.0 como objeto de estudio emergente, en diálogo con una metodología consolidada como el LSS, y busca, a través de un enfoque mixto, contribuir tanto al desarrollo teórico como a la implementación efectiva del nuevo paradigma industrial.

A continuación, se describen brevemente los artículos.

1.2. Sinergias entre Industria 5.0 y Lean Six Sigma

El primer artículo que compone esta tesis lleva por título *“Industry 5.0’s pillars and Lean Six Sigma: mapping the current interrelationship and future research directions”* y ha sido publicado en una revista de reconocido impacto en el ámbito de la gestión y la ingeniería industrial (SJR 2024: 0.954, Q1; H-index: 83). Su objetivo principal es analizar la convergencia conceptual y práctica entre los pilares de la I5.0 y la metodología LSS, tradicionalmente asociada a la mejora continua, la eficiencia operativa y la calidad organizativa (Pepper and Spedding, 2010).

Para ello, se adoptó un enfoque metodológico de carácter exploratorio y cualitativo, estructurado en tres fases interdependientes: revisión sistemática de la literatura científica, análisis bibliométrico de redes y validación mediante consulta experta.

En la primera fase, se constató la inexistencia de estudios previos que abordaran de forma directa la relación entre I5.0 y LSS. Ante esta carencia, se procedió a realizar una revisión sistemática en las principales bases de datos académicas con el fin de identificar literatura relacionada que analizara los vínculos entre cada uno de los tres pilares de la I5.0 —sostenibilidad, enfoque humano y resiliencia— y las prácticas, principios o herramientas propias del LSS.

La segunda fase consistió en el desarrollo de un análisis bibliométrico mediante técnicas de co-ocurrencia de palabras clave, lo que permitió identificar clústeres temáticos, patrones emergentes y relaciones conceptuales latentes en el campo. Este ejercicio de mapeo bibliográfico evidenció la existencia de zonas de intersección aún poco desarrolladas entre ambas aproximaciones y sirvió para estructurar una visión más precisa sobre el grado de alineamiento conceptual entre I5.0 y LSS.

La última fase correspondió a la validación cualitativa mediante entrevistas semiestructuradas a un panel internacional de expertos con experiencia reconocida en LSS, transformación digital e implantación de iniciativas alineadas con los principios de la I5.0. Estas entrevistas permitieron contrastar los hallazgos derivados del análisis documental, enriquecer la interpretación de los resultados e incorporar una mirada aplicada sobre la compatibilidad y complementariedad entre ambos enfoques.

Los resultados del estudio muestran que existen sinergias significativas entre los pilares de la I5.0 y el LSS. En el ámbito de la sostenibilidad**,** LSS contribuye a través de la reducción sistemática de residuos, la optimización de recursos y el fomento de prácticas de manufactura verde (Souza *et al.*, 2022). En cuanto al enfoque humano-céntrico**,** LSS promueve entornos colaborativos, el desarrollo continuo de competencias, la participación activa del personal y la interacción efectiva entre operarios y sistemas automatizados (Benkhati *et al.*, 2023). En el pilar de la resiliencia**,** se observan contribuciones relacionadas con el diseño de estructuras organizativas flexibles, la gestión proactiva del riesgo y la capacidad de respuesta ante escenarios disruptivos (Ince *et al.*, 2023; Thakur-Weigold and Miroudot, 2024).

No obstante, también se identifican diferencias significativas: mientras que LSS mantiene su foco en la eficiencia operativa y la creación de valor para el cliente, la I5.0 amplía dicho horizonte al incorporar objetivos explícitos relacionados con el bienestar social, la sostenibilidad medioambiental y la robustez sistémica a largo plazo. Esta divergencia no implica una contradicción, sino más bien una oportunidad de complementariedad estratégica.

La principal contribución de este estudio radica en posicionar a LSS no únicamente como una herramienta de mejora continua, sino como una palanca estratégica capaz de facilitar la transición hacia la I5.0**.** Este planteamiento revaloriza el papel de LSS en la era posdigital, sugiriendo su utilidad para alcanzar los valores que promueve la I5.0. Asimismo, el artículo abre nuevas líneas de investigación para el establecimiento de marcos regulatorios en la industria y la elaboración de hojas de ruta que permitan implementar la I5.0 con la asistencia del LSS.

1.3. Modelo de evaluación de la preparación organizacional hacia la Industria 5.0

El segundo artículo, titulado *"Assessment model for Industry 5.0: A holistic approach to readiness and integration"*, ha sido publicado por una revista indexada de reconocido impacto en el ámbito de la ingeniería industrial y manufactura (SJR 2024: 2.445, Q1; H-index: 62). Esta contribución rellena el vacío académico de la inexistencia de modelos de evaluación específicos que permitan diagnosticar, de forma general y sistemática, el grado de preparación de una organización para transitar hacia la I5.0.

La investigación parte del reconocimiento de que, a diferencia del enfoque predominantemente tecnológico de la Industria 4.0, la I5.0 enfatiza la integración equilibrada entre sistemas técnicos y humanos. Por esta razón, se adoptó como marco teórico la Teoría Socio-Técnica (TST), desarrollada originalmente por Trist (1981), que propone que el desempeño organizacional óptimo solo puede alcanzarse mediante la co-optimización simultánea de los subsistemas sociales y técnicos. Este enfoque resultó especialmente pertinente para fundamentar un modelo que pretendía capturar no solo las capacidades tecnológicas, sino también aspectos organizativos, culturales y humanos que condicionan la adopción efectiva de la I5.0.

El desarrollo del modelo se llevó a cabo en dos fases. La primera fase, de carácter conceptual, se centró en la construcción del marco teórico a partir de una revisión sistemática de literatura. Esta revisión permitió identificar y sintetizar tanto los conocimientos relevantes en torno a los fundamentos del paradigma I5.0, como los modelos de madurez y evaluación aplicados en contextos industriales. Como complemento, se aplicó un análisis bibliométrico de redes de co-ocurrencia para visualizar las interconexiones entre conceptos clave y reforzar la estructuración lógica del modelo. Esta triangulación documental permitió organizar las dimensiones emergentes en torno a los pilares de la I5.0.

La segunda fase se orientó al refinamiento y validación del modelo preliminar. Para ello, se desarrolló la validación por un panel multidisciplinar de expertos compuesto por profesionales del sector industrial y académicos especializados en transformación digital, sostenibilidad y gestión organizacional. A través de este grupo se buscó evaluar la claridad, pertinencia y aplicabilidad de cada una de las dimensiones propuestas, asegurando así la relevancia práctica del modelo para diferentes contextos organizacionales. El proceso de retroalimentación recogido permitió realizar ajustes, redefinir algunas categorías y garantizar que el instrumento resultante no solo fuera sólido desde el punto de vista teórico, sino también funcional para su uso operativo.

El modelo de evaluación final se estructura en torno a cuatro grandes áreas: sostenibilidad, enfoque humano-céntrico, resiliencia organizativa y elementos transversales. Estas áreas se desagregan en 25 dimensiones críticas y 64 preguntas guía, que permiten evaluar de manera desagregada el nivel de preparación de una organización en relación con los principios de la I5.0. De este modo, el modelo funciona como una herramienta estratégica que posibilita a las organizaciones: (i) diagnosticar su estado inicial frente a los requisitos del nuevo paradigma, (ii) establecer objetivos estratégicos alineados con los valores de la I5.0 y (iii) planificar la asignación de recursos y la adopción progresiva de las capacidades necesarias.

Más allá de su aplicabilidad inmediata, esta propuesta metodológica contribuye al desarrollo de líneas futuras de investigación de gran interés como son el análisis longitudinal del impacto de la implementación del modelo en el desempeño organizacional, la comparación sectorial entre empresas con distintos niveles de madurez, y la exploración sobre su incorporación en marcos regulatorios o certificaciones industriales.

1.4. Barreras para la adopción de la Industria 5.0 y el papel del Lean Six Sigma en su mitigación

El tercer artículo lleva por título *"Barriers to Industry 5.0 adoption and perception-based differences between Lean and non-Lean Six Sigma firms"* y se encuentra en proceso de evaluación, en una revista de reconocido impacto del ámbito de la estrategia y gestión organizacional (SJR 2024: 1.134, Q1; H-index: 117).

Esta investigación aborda la cuestión clave de la identificación de las barreras críticas que pueden obstaculizan la adopción de la I5.0 en entornos organizativos, así como el potencial del LSS como mecanismo de mitigación de esas barreras. Además, el estudio incorpora un análisis comparado de dos casos de empresas para explorar si la experiencia previa con LSS influye en la forma en que las organizaciones perciben dichas barreras.

El diseño metodológico adoptado responde a un enfoque mixto y secuencial, estructurado en tres fases complementarias. En primer lugar, se aplicó un estudio Delphi de dos rondas con un panel internacional de expertos procedentes de diversos sectores industriales. Esta técnica permitió alcanzar un consenso estructurado sobre las principales barreras a la adopción de la I5.0, priorizando aquellas que representan mayores obstáculos en términos de percepción, impacto y dificultad de superación. En segundo lugar, se realizó una revisión sistemática de literatura con el objetivo de contrastar y enriquecer las barreras identificadas empíricamente, asegurando la consistencia con los hallazgos académicos previos y ampliando el espectro de análisis. Finalmente, se llevaron a cabo estudios de caso comparativos en dos organizaciones con características contrastantes: una empresa con una trayectoria consolidada en la aplicación de LSS y otra empresa sin experiencia previa en metodologías de mejora continua. En ambos casos, se emplearon entrevistas personales semiestructuradas con perfiles directivos y técnicos, así como la aplicación de escalas Likert para valorar la severidad percibida de las barreras y la capacidad organizacional para abordarlas.

Este enfoque triangulado permitió mejorar la validez de los resultados mediante la convergencia de fuentes múltiples, y proporcionó una mayor comprensión de los desafíos que enfrenta la implementación de la I5.0 en contextos empresariales (Ivert and Jonsson, 2010).

Como resultado, se elaboró un marco analítico y práctico orientado a ayudar tanto a organizaciones como a investigadores y responsables de políticas públicas en la comprensión y superación de dichos obstáculos. Entre las barreras más relevantes identificadas destacan: la escasez de recursos financieros, la complejidad técnica y metodológica para realizar evaluaciones de ciclo de vida, la resistencia cultural al cambio organizacional, y la ausencia de marcos regulatorios específicos que guíen la adopción de la I5.0.

A partir de estas barreras priorizadas, se identificaron herramientas específicas de LSS que podrían ayudar a mitigarlas. Por ejemplo, el uso de DMAIC y Kaizen para estructurar mejoras continuas de procesos; Value Stream Mapping para identificar cuellos de botella y optimizar flujos de valor; FMEA y simulación Monte Carlo para gestionar riesgos asociados a la transformación digital; y herramientas como Skills Matrix y el Modelo de los 8 Pasos de Kotter para facilitar la transformación cultural y el desarrollo de competencias organizacionales clave.

Un hallazgo especialmente relevante del estudio es que la organización con experiencia previa en LSS percibió las barreras para la implementación de la I5.0 como menos severas que aquellas que la que carecía de dicha trayectoria. Esta diferencia perceptual sugiere que el LSS no solo actúa como facilitador, sino que también puede constituir un catalizador cultural y estratégico en el proceso de transición hacia un modelo industrial más sostenible, centrado en las personas y resiliente.

A partir de los resultados obtenidos, surgen dos líneas de investigación principales. La primera se orienta a replicar y contrastar estos hallazgos en diferentes sectores industriales, contextos geográficos y marcos culturales, lo que permitiría evaluar la generalización del modelo propuesto. La segunda línea propone una profundización en la aplicación de herramientas LSS y el análisis comparativo con otras metodologías de mejora continua para evaluar su eficacia relativa en la mitigación de las barreras.

1.5. Complementariedad entre los artículos

Esta investigación se estructuró siguiendo una línea secuencial que evolucionara desde la fundamentación teórica de la relación entre la I5.0 y el LSS hasta su aplicación práctica.

En el primer trabajo asentamos las bases de la investigación al justificar los motivos por los que la metodología LSS es intrínsecamente relevante y potencialmente facilitadora para la implementación de la I5.0.

Continuando con esta progresión, en el segundo trabajo nos adentramos en la cuestión de qué evaluar, para proponer un modelo para cuantificar la preparación y el progreso de una organización hacia la adopción de I5.0.

Finalmente, en el tercer trabajo abordamos el desafío práctico de cómo identificar y superar los obstáculos que puedan surgir durante la transición a la I5.0. Este trabajo no solo cataloga las barreras, sino que también sugiere herramientas específicas de LSS para mitigarlas.

En resumen, cada etapa de la investigación se ha construido sobre los hallazgos de la anterior, asegurando así una progresión en la que los hallazgos de cada artículo complementan y validan los del siguiente, consolidando su aporte tanto en términos teóricos como prácticos.

2. METODOLOGÍA DE INVESTIGACIÓN

El diseño metodológico ha sido concebido con el propósito de abordar las principales lagunas detectadas en la literatura sobre la I5.0 y su convergencia con el LSS. Actualmente, la producción científica se organiza en torno a tres ejes principales: (i) estudios que abordan los fundamentos conceptuales de la I5.0 y están centrados en la descripción de sus pilares sin establecer mecanismos operativos de implementación (Breque *et al.*, 2021; Maddikunta *et al.*, 2022; Xu *et al.*, 2021), (ii) una literatura consolidada sobre LSS respecto a su eficacia en la mejora de la eficiencia y calidad organizativa (Elkhairi *et al.*, 2022), pero que posee escasa vinculación con los principios de la I5.0; y (iii) contribuciones que mencionan barreras a la implementación de la I5.0 pero que se encuentran fragmentados y que no las conectan con herramientas que pudieran facilitar su superación (Maddikunta *et al.*, 2022).

Esta situación evidencia tres lagunas significativas en el cuerpo de conocimiento: la exploración de sinergias entre I5.0 y metodologías consolidadas como el LSS; la ausencia de modelos de evaluación para organizaciones; y la identificación de las posibles barreras, así como la disponibilidad de herramientas prácticas orientadas a mitigar esas barreras durante su adopción.

Para dar respuesta a estas lagunas, se diseñó una metodología mixta que partió de la revisión sistemática de literatura agregada, el análisis de redes bibliográficas y la revisión sistemática detallada de la literatura, continuó con la validación por expertos y la metodología Delphi, y finalizó con estudios de casos.

En la Revisión Sistemática de Literatura Agregada recopilamos el conocimiento existente y evaluamos el estado actual del campo de estudio (Kunisch *et al.*, 2018). Esta revisión nos facilitó el desarrollo teórico, mostró las áreas que poseían suficiente investigación e identificó las áreas que requieren mayor investigación (Webster and Watson, 2002). También nos permitió evaluar el estado de madurez del campo e identificar las preguntas de investigación que permanecían sin contestar (Kraus *et al.*, 2020).

Las bases de datos utilizadas fueron WoS, Scopus, Emerald, Science Direct, EBSCOhost, y ProQuest, restringiendo la búsqueda a artículos peer-reviewed o early access y publicados en inglés. Se excluyeron aquellos trabajos cuyo concepto de I5.0 o LSS no coincidía con el comúnmente aceptado o tan solo se mencionan tangencialmente.

Utilizamos el Análisis de Redes Bibliográficas para identificar coincidencias entre las palabras clave de los autores y, de esta manera, resumir la estructura intelectual, las tendencias emergentes, los temas recurrentes y los patrones en el campo (Bhatt *et al.*, 2020). Sus resultados nos proporcionaron información sobre el estado actual del conocimiento, su evolución temporal, sus interrelaciones y las preguntas de investigación que deberían abordarse.

El tipo de análisis fue el acoplamiento bibliográfico sobre la co-ocurrencia y palabras clave del autor, utilizando VOSviewer como software de trabajo (van Eck and Waltman, 2010). Los investigadores reconocen esta herramienta como un enfoque estándar en las revisiones de la literatura para resaltar temas y tendencias emergentes de naturaleza sociotécnica como la de I5.0 (Rani and Salanke, 2023).

Este análisis nos permitió identificar los factores críticos que componen las diversas áreas de la I5.0, elucidando así los componentes fundamentales del conocimiento existente (Radhakrishnan *et al.*, 2017).

La Revisión Sistemática Detallada de la Literatura posibilitó identificar las relaciones entre la I5.0 y el LSS, y extraer las ideas más comunes, completar la identificación de lagunas en la investigación, establecer las preguntas de investigación finales, y sintetizar la literatura relacionada con estas preguntas (Barley *et al.*, 2017; Endo *et al.*, 2014)**.** Estas revisiones, centradas en los resultados obtenidos en WoS y Scopus, nos permitieron establecer los resultados preliminares al identificar, clasificar y resumir los aspectos relevantes y los marcos de evaluación propuestos para la I5.0, conforme a las recomendaciones de Brocke et al. (2009).

La Validación por Expertos, utilizada en el primer artículo, implicó la colaboración con expertos tanto en I5.0 como en LSS, según lo recomendado por Beecham et al. (2005). A partir de bases de datos académicas y otras publicaciones, reunimos un panel internacional de 12 expertos que procedían de Brasil (2), Egipto (1), Irán (1), Polonia (2), Portugal (2), España (3) y Taiwán (1). Este panel estuvo compuesto por cuatro profesionales, dos consultores y seis académicos. Sus comentarios se recopilaron mediante intercambios de correo electrónico y entrevistas por videoconferencia de aproximadamente 45 minutos cada una.

Para el segundo artículo, el panel de expertos se seleccionó en base a su amplio conocimiento de la I5.0, y su experiencia gerencial y operativa. Estos criterios garantizaron valiosas perspectivas para la implementación práctica del paradigma (Seuring *et al.*, 2021). Se entrevistó a un total de 12 especialistas de seis campos diferentes para obtener una amplia gama de perspectivas: centros tecnológicos (2), clústeres industriales (1), iniciativas I5.0 (5), consultorías (2), parques empresariales (1) y escuelas de negocios (1).

En el tercer artículo se empleó la metodología Delphi para recopilar y cuantificar las opiniones de expertos sobre las barreras durante la implementación de la I5.0. Se aplicó la técnica de von der Gracht (2012), ampliamente utilizada para recopilar opiniones de expertos sobre desarrollos futuros. El panel lo conformaron 19 expertos seleccionados por su experiencia y conocimientos en I5.0, garantizando la representación de empresas de todos los tamaños, industrias, sectores, ubicaciones geográficas y etapas de implementación de I5.0.

En la primera ronda, identificaron las barreras que las organizaciones pueden encontrar durante la implementación de I5.0. Esta identificación inicial de barreras se perfeccionó mediante una revisión bibliográfica. En la segunda ronda, se cuantificaron las barreras y los expertos aportaron información adicional. Finalmente, tras un análisis de los comentarios recibidos, se estableció el modelo de evaluación para la I5.0 (Dieste *et al.*, 2022).

Debemos señalar que tuvimos dificultades en conformar los paneles de expertos dado el estado incipiente de la I5.0. Aunque el tamaño del panel no es extenso, esta situación se puede considerar una práctica común en las primeras etapas de investigación (Hakim, 1987), y ha sido utilizada en estudios similares, como el de Dybå (2000), quien consultó a 11 expertos en una revisión similar.

La última técnica empleada consistió en un estudio de caso en dos empresas para explorar en mayor profundidad los resultados identificados mediante la metodología Delphi y la revisión bibliográfica. Utilizamos el estudio de caso dado nuestro objetivo de comprender, describir e ilustrar los desafíos que se enfrentan las empresas al adoptar la I5.0 y considerando nuestra posición externa como investigadores. Este enfoque se alinea con la clasificación de Martinsuo and Huemann, (2021), que aboga por estudios de caso para explorar en profundidad fenómenos prácticos complejos.

Dado que nuestra investigación trata sobre un fenómeno contemporáneo en su contexto, y que los límites entre el fenómeno y el contexto no están claramente definidos, nos basamos en la metodología de indagación propuesta por Yin (2018) y consideramos el análisis de dos empresas. La primera empresa, filial de una multinacional farmacéutica, contaba con una sólida trayectoria en LSS (15 años de experiencia), 520 empleados y un entorno altamente regulado. La segunda empresa, una minorista del sector del diseño y la distribución, carecía de experiencia en LSS, pero presentaba una estructura ágil y una cadena de suministro externalizada, con 93 empleados y fuerte orientación al crecimiento. Justificamos la selección de estas dos empresas debido a sus diferentes contextos industriales, estructuras operativas y niveles de madurez de LSS.

La primera empresa fue elegida debido a su entorno regulatorio, su alta complejidad de fabricación y su amplia experiencia con LSS. Su consolidada cultura de optimización de procesos y su enfoque estructurado de mejora continua resultaban ideales para evaluar cómo las prácticas de excelencia operativa podrían influir en la adopción de la I5.0. El minorista textil representa una industria más dinámica, impulsada por el diseño, con un rápido crecimiento y la externalización de la cadena de suministro, lo que permite examinar las barreras de la I5.0 en un sector menos orientado a los procesos y altamente competitivo, donde la agilidad y la adaptabilidad son cruciales. Ninguna de las empresas tenía conocimiento previo del paradigma I5.0, aunque ambas demostraron una sólida comprensión de sus pilares (sostenibilidad, personas y resiliencia).

Las unidades de observación fueron tres directores de cada empresa: Recursos Humanos, Sostenibilidad y LSS en la Empresa 1; Recursos Humanos, Sostenibilidad y Logística en la Empresa 2. Estos profesionales fueron las principales fuentes de datos que nos permitieron realizar un análisis comparativo intra-empresa (dentro de cada organización) e inter-empresas (entre la empresa con y sin LSS), lo que facilitó la identificación de patrones, diferencias en las percepciones y las estrategias de mitigación, siguiendo adopciones similares como la de Amin et al. (2025).

Elegimos estos tres puestos directivos para la observación debido a su participación directa en los tres pilares de la I5.0. Recursos Humanos es crucial para la implementación de la I5.0, ya que supervisa la adaptación de la fuerza laboral, el desarrollo de habilidades y la gestión del cambio. Dado el fuerte énfasis de la I5.0 en la centralidad humana, este puesto proporciona información valiosa sobre los desafíos del compromiso de los empleados, la capacitación y la transformación laboral. El responsable de Sostenibilidad proporciona información sobre el cumplimiento normativo, las prácticas de fabricación ecológica y las iniciativas de economía circular, lo que ayuda a identificar las barreras que afectan a las operaciones sostenibles, la eficiencia de los recursos y la responsabilidad corporativa a largo plazo.

En la primera empresa, entrevistamos al responsable de LSS debido a la amplia trayectoria en la implementación de LSS. Este puesto aporta experiencia en optimización de procesos, gestión de calidad y mejoras de eficiencia, factores cruciales para comprender los desafíos operativos de la adopción de la I5.0. Dado que la agilidad de la cadena de suministro y la eficiencia de la distribución son fundamentales en la empresa minorista, elegimos al responsable de Logística. Esta posición garantiza la identificación de las barreras a la externalización, la coordinación de la cadena de suministro y la integración de los principios de la I5.0 en un entorno minorista dinámico.

El análisis de estas tres posiciones gerenciales en ambas empresas garantiza un enfoque multidisciplinar equilibrado, que identifica las barreras humanas, ambientales y operativas. Esta metodología contribuye a confirmar los hallazgos del grupo Delphi y permite comparar diferentes puntos de vista dentro de la misma empresa y entre las empresas.

Realizamos entrevistas presenciales en tres fases. En primer lugar, los participantes evaluaron cuantitativamente la preparación de la empresa para la implementación de la I5.0. En segundo lugar, cuantificaron la importancia de cada barrera en su contexto organizacional. En tercer lugar, el responsable de LSS exploró las posibles herramientas para superar cada barrera identificada.

Para cada barrera, calculamos el promedio (AVE) y el rango (RAN) utilizando IBM SPSS para cuantificar la importancia percibida y la variabilidad entre los participantes. El AVE proporcionó una medida central de la importancia que los participantes consideraban de cada barrera, y el RAN el grado de divergencia en las opiniones de los expertos, destacando las áreas de consenso/desacuerdo.

Para enriquecer la valoración cuantitativa, realizamos entrevistas semiestructuradas, adaptando ligeramente las preguntas para incorporar diversos puntos de vista, siguiendo las recomendaciones de Yin (2018) para la investigación de estudios de caso. Este enfoque permitió una comprensión más detallada de cómo las organizaciones perciben y experimentan estos desafíos en la práctica y ha demostrado su validez en estudios similares de adopción de tecnología, p. ej., Amin et al. (2025). Finalmente, documentamos y analizamos colaborativamente los comentarios realizados.

Como afirma Ivert and Jonsson (2010), este enfoque multifacético mejora la confiabilidad de los hallazgos a través de la triangulación y produce una comprensión más profunda de los desafíos complejos asociados con la adopción de I5.0.

Finalmente, señalar que se priorizó que los resultados pudieran ser aplicados en organizaciones de distintos tamaños, sectores y niveles de madurez. A modo de ejemplo, el modelo de evaluación permite a cualquier organización realizar su diagnóstico y planificar su transición. Del mismo modo, las herramientas de LSS sugeridas para superar las barreras están altamente contrastadas y son aplicables en múltiples industrias.

De este modo, la metodología empleada no solo se justifica por el conocimiento teórico generado, sino que también destaca por su utilidad en la transferencia de ese conocimiento al entorno profesional.

3. DISCUSIÓN Y CONCLUSIONES

Esta tesis doctoral ha desarrollado una línea de investigación cuyo propósito ha sido avanzar desde los fundamentos conceptuales hacia la implementación práctica de la I5.0. A lo largo de los tres estudios complementarios, se ha construido un cuerpo de conocimiento orientado a facilitar la comprensión, cuantificación e implementación de los principios de la I5.0.

En el primer trabajo, se constató la inexistencia de una vinculación directa entre la I5.0 y el LSS en la literatura actual. Sin embargo, el análisis realizado mostró conexiones directas entre el LSS y cada uno de los pilares de la I5.0. Este análisis ratificó el potencial del LSS para respaldar los principios de la I5.0 dado sus numerosas similitudes conceptuales y estratégicas. Entre sus resultados, podemos mencionar la necesidad de un liderazgo fuerte, la búsqueda de eficiencia, la reducción de desperdicios, la promoción de la sostenibilidad (Benkhati *et al.*, 2023) la priorización de la participación de los empleados, la capacitación, el trabajo en equipo y la colaboración entre personas y máquinas (Margherita and Zabudkina, 2023), así como la necesidad de adaptabilidad ante eventos impredecibles (Thakur-Weigold and Miroudot, 2024).

También se encontraron diferencias clave en aspectos como los marcos regulatorios (Mollenkopf *et al.*, 2010), el enfoque estratégico, las hojas de ruta de implementación, las herramientas de evaluación disponibles, la definición de valor y los requerimientos de inversión (Leng *et al.*, 2022).

El estudio concluyó que el LSS tiene el potencial de promover la adopción de la I5.0 gracias a su metodología estructurada, cultura de mejora continua, enfoque en la gestión de riesgos y la colaboración personas-máquinas (Badhotiya *et al.*, 2024).

Adicionalmente, se constató la propia capacidad del LSS para ampliar sus actuales aplicaciones a la triple línea de base -social, económica y ambiental- (Wadood *et al.*, 2023), mejorar la centralidad humana al fomentar el desarrollo y la participación de los trabajadores (Klein *et al.*, 2023), y fortalecer la resiliencia organizacional a través de una mejor toma de decisiones y la optimización de procesos (Ince *et al.*, 2023).

El segundo estudio abordó la ausencia de modelos de evaluación para cuantificar la preparación organizacional hacia la I5.0. Su validación por expertos destacó su utilidad como instrumento de implementación y alineación estratégica.

También identificó las cuatro áreas fundamentales que estructuran el modelo de evaluación: aspectos generales, sostenibilidad, centralidad humana y resiliencia. Dentro de estas áreas, se establecieron 25 dimensiones críticas, cada una acompañada de preguntas guía que permiten a las organizaciones evaluar su nivel de madurez e identificar áreas clave de mejora.

Este modelo resulta ser una valiosa herramienta práctica para que las organizaciones evalúen su estado de madurez en la adopción de la I5.0, identifiquen áreas de mejora y detecten los elementos clave para una transición exitosa, ayudándoles a alinear sus estrategias y asegurar su adaptabilidad en un entorno industrial dinámico.

El tercer estudio identificó y analizó las barreras para la adopción de la I5.0, diferenciando su percepción según el grado de madurez en LSS. La primera ronda del estudio Delphi y la revisión de la literatura identificaron una lista detallada de barreras para la I5.0, agrupadas en cuatro áreas: sostenibilidad (p. ej., integración de economía circular, huella de carbono) (Adel, 2022), centralidad humana (p. ej., adaptación de la fuerza laboral, necesidad de capacitación y nuevas habilidades) (Alves *et al.*, 2023), resiliencia (p. ej., desarrollo de procesos flexibles, gestión de riesgos) (Sindhwani *et al.*, 2022), y aspectos generales (p. ej., desalineación con modelos de negocio, falta de marcos regulatorios claros, restricciones financieras) (Grabowska, 2022).

La segunda ronda del Delphi cuantificó la importancia de estas barreras, destacando la alta criticidad de los marcos regulatorios, la presión del cliente, la atracción y retención de talento, y el desarrollo de estrategias de resiliencia. El estudio de casos proporcionó una visión empírica, comparando una empresa con experiencia en LSS y otra sin ella. Se observaron diferencias en la priorización de barreras (p. ej., la primera empresa priorizó la resiliencia, mientras que la segunda se centró en la evaluación del ciclo de vida y la competitividad global), lo que sugiere que la cultura organizacional y la experiencia previa con el LSS influyen en la percepción y gestión de estos obstáculos.

Finalmente, se propuso la aplicación de herramientas LSS para mitigar las barreras identificadas. Las herramientas más recomendadas incluyeron DMAIC, Mapeo del Flujo de Valor (VSM) y Kaizen para la optimización de procesos y reducción de desperdicios, además de otras como FMEA, SIPOC y PDCA para la resolución de problemas y gestión de riesgos. Herramientas como Design for Six Sigma, Hoshin Kanri, Análisis Coste-Beneficio y Kotter's 8-Step Change Model fueron sugeridas para abordar desafíos financieros, estratégicos y de cambio cultural en la transición a la I5.0.

Es importante destacar que estos resultados deben entenderse en el marco de un campo en construcción. La I5.0, como paradigma emergente, ha sido hasta el momento objeto de exploraciones principalmente teóricas. Esta investigación trasciende ese enfoque al integrar teoría, diseño de modelos y aplicación práctica.

Complementariamente, se destacó el papel fundamental de los gobiernos y los responsables de formulación de políticas para establecer marcos regulatorios claros e invertir en la fuerza laboral y en las infraestructuras necesarias. Resaltar, por ejemplo, que las barreras regulatorias y financieras son percibidas como más críticas que las tecnológicas, destacando la necesidad de políticas públicas activas para superarlas.

En resumen, la tesis subraya que la I5.0 representa un cambio transformador que trasciende a la automatización de la Industria 4.0 (Ghobakhloo *et al.*, 2024) y que la aplicación del LSS no solo optimiza los sistemas técnicos, sino que también fomenta la sostenibilidad, el bienestar humano y la resiliencia en un entorno industrial dinámico e impredecible (Jäpel *et al.*, 2024).

3.1. Contribución a la teoría

Desde una perspectiva teórica, la presente tesis proporciona información valiosa sobre la I5.0 y amplía sus conocimientos, promoviendo el diálogo académico y avanzando la comprensión teórica en varias áreas clave.

En primer lugar, ofrece un análisis pionero de la convergencia entre la I5.0 y el LSS, sentando las bases teóricas para consolidar esta relación.

También complementa diversos estudios previos como por ejemplo, la integración del LSS con la Industria 4.0 en el marco de I5.0 (Moraes *et al.*, 2023), la conexión entre LSS y el enfoque centrado en el ser humano de la I5.0 (Rahardjo *et al.*, 2023), la relación entre la I5.0 y el TQM (Chaabi, 2022), los vínculos entre el LSS y la Industria 4.0 (Ejsmont *et al.*, 2020), la transición del LSS y la Industria 4.0 hacia la I5.0 (Eriksson *et al.*, 2024) y los marcos para la integración del LSS con la Industria 4.0 (Skalli *et al.*, 2024).

Por otro lado, expande el campo del LSS más allá de la eficiencia operativa, posicionándolo como una metodología valiosa de mejora hacia nuevas dimensiones (sostenibilidad, ética, resiliencia, empoderamiento humano) que no eran centrales en los enfoques previos. En este mismo sentido, también expande su utilidad al facilitar la superación de los obstáculos en la implantación de la I5.0 aplicando sus herramientas.

Además, resuelve el problema de la ausencia de marcos de evaluación adaptados a los principios concretos de la I5.0. El modelo resultante no solo cierra la brecha socio-técnica al optimizar conjuntamente los sistemas humanos y tecnológicos, sino que también enriquece el discurso teórico sobre la relación de la industria con la sostenibilidad, la colaboración humano-máquina, y la resiliencia organizacional.

Es importante resaltar que disponer de un modelo de evaluación presenta otra contribución fundamental: la I5.0 es un paradigma novedoso que está en construcción y no existe un consenso sobre su definición concreta ni sobre su alcance. Disponer de este modelo contribuye a establecer sus componentes concretos y, por ejemplo, a diferenciar entre organizaciones I5.0 y las que no lo son.

Finalmente, avanza en la comprensión teórica de las barreras a la implementación de la I5.0, un aspecto en el que la literatura actual se encontraba fragmentada y no existía consenso sobre la importancia de las diferentes barreras. Este avance resulta especialmente importante dado que esta investigación conecta marcos teóricos con realidades de gestión en el contexto de un paradigma emergente.

3.2. Contribución a la práctica

Esta tesis proporciona información práctica para todos los integrantes de la quíntuple hélice: industria, gobierno, academia, público y medioambiente (Carayannis and Morawska-Jancelewicz, 2022).

El estudio dota a los responsables de las organizaciones de la información sobre los beneficios y desafíos asociados con la integración de la I5.0 con el LSS y, por lo tanto, les ofrece herramientas para la toma de decisiones estratégicas adecuadas. En especial, los resultados ofrecen una comprensión más profunda de la resiliencia y de la adaptabilidad organizacional frente al cambio tecnológico con vistas a optimizar sus procesos dentro del marco de la I5.0.

El modelo de evaluación resulta una herramienta indispensable para guiar a las organizaciones a través de la transición hacia la I5.0. Este modelo permite a las empresas comprender el grado de modernización necesario para la I5.0 (Alojaiman, 2023), identifica los factores clave para una transición exitosa (Trstenjak *et al.*, 2023), y clasifica su nivel actual de preparación para facilitar una planificación estratégica eficaz de la adaptación (Hein-Pensel *et al.*, 2023).

También proporciona información práctica a las organizaciones que buscan aprovechar las sinergias del LSS mientras abordan las complejidades de la implementación de la I5.0.

En este sentido, los resultados sobre las barreras a la implantación de la I5.0 resultan especialmente valiosos puesto que ofrecen la información necesaria a los directivos para acometer las barreras de adopción.

Además, tiende un puente entre la política y la industria, informando sobre las iniciativas de apoyo gubernamental (políticas, regulaciones, estándares e incentivos públicos) que se alineen con las necesidades industriales. Concretamente, se insta a los responsables políticos a definir proactivamente marcos regulatorios que faciliten la convergencia de la I5.0 y el LSS para promover la innovación, la sostenibilidad, la mejora social y la resiliencia.

Por otro lado, la identificación de las barreras para la implantación de la I5.0 es un requisito básico para que los responsables políticos puedan establecer las iniciativas y las ayudas adecuadas.

Un tema recurrente en las interacciones con los participantes ha sido el papel fundamental de los responsables políticos para facilitar la adopción de la I5.0. Este papel incluye establecer marcos regulatorios y estándares claros para la I5.0, ofrecer incentivos financieros, invertir en programas de educación y capacitación para desarrollar una fuerza laboral cualificada en I5.0, y promover la concienciación y la comprensión de sus beneficios para la sociedad y las empresas.

Desde el punto de vista de la investigación, este estudio contribuye a explorar enfoques interdisciplinarios e iniciativas colaborativas con el objetivo de avanzar en las aplicaciones prácticas relacionadas con la alineación de los principios de la I5.0 con las necesidades y las mejores prácticas de la industria. Esta alineación no solo beneficia a las organizaciones, sino que también fortalece el ecosistema industrial en su conjunto al fomentar la innovación y apoyar el crecimiento sostenible de las organizaciones.

Respecto a las instituciones educativas, los hallazgos resaltan la importancia de adaptar sus programas para transferir eficazmente tanto los conocimientos teóricos como las habilidades prácticas con el objetivo de adoptar una cultura de mejora continua, invertir en el desarrollo de la fuerza laboral y adoptar estrategias formativas que permitan abordar las complejidades eficazmente.

Dicho desarrollo permite a los profesionales formativos diseñar programas de capacitación que doten, tanto a los futuros empleados como de los que actualmente están en activo, de las habilidades necesarias para operar eficazmente en este entorno. Estas habilidades deben incluir tanto habilidades técnicas relacionadas con las tecnologías como habilidades interpersonales como el pensamiento crítico, la resolución de problemas y la colaboración.

La contribución de este estudio a la práctica de la sostenibilidad es múltiple. En primer lugar, destaca la necesidad de integrar la sostenibilidad en los procesos de transformación digital que están acometiendo las organizaciones, avanzando más allá del retorno económico o la maximización del valor para los accionistas, y posicionándola como un factor estratégico generador de ventaja competitiva.

El estudio proporciona herramientas concretas del LSS que permiten alcanzar el pilar de la sostenibilidad de la I5.0. Estas herramientas, como el Value Stream Mapping, el enfoque de los 7+1 Wastes o los análisis de ciclo de vida, facilitan la reducción de residuos, la mejora en la eficiencia del uso de los recursos y la implementación de principios de economía circular.

Asimismo, la disponibilidad de un modelo de evaluación específico permite a los equipos directivos diagnosticar el punto de partida ambiental de sus organizaciones y diseñar estrategias sostenibles alineadas con sus objetivos. De igual forma, el conocimiento de las barreras críticas facilita la planificación proactiva, reduciendo los riesgos de implementación y mejorando su capacidad de adaptación.

También ayuda a la gobernanza empresarial en su transición a políticas más sostenibles y participativas, al identificar ámbitos prioritarios de intervención como la gestión eficiente de los recursos, la adopción de modelos circulares o la integración de criterios ambientales en la toma de decisiones.

Adicionalmente, amplía de forma importante el campo de actuación de los profesionales del LSS, tradicionalmente centrado en la eficiencia operativa, posicionándolos como actores clave en la transición hacia una industria más responsable desde el punto de vista medioambiental.

Por último, queremos señalar que los resultados de esta investigación contribuyen a objetivos de sostenibilidad global como los Objetivos de Desarrollo Sostenible, y más concretamente, a políticas prioritarias de la Unión Europea como el European Green Deal (European Commission, 2023), An Economy that Works for People (European Commission, 2020a) y A Europe Fit for the Digital Age (European Commission, 2020b). Estos marcos estratégicos encuentran en esta tesis una base operativa para su materialización en el ámbito empresarial.

3.3. Limitaciones

Una de las principales limitaciones reside en la naturaleza emergente del campo de la I5.0. Dado que es un paradigma novedoso, la literatura científica existente aún es escasa, lo que limitó el tamaño y la profundidad del corpus bibliográfico inicial.

Otra limitación fue la escasez de expertos y organizaciones con un conocimiento profundo en I5.0 y, sobre todo, de conocimientos conjuntos de I5.0 y LSS. Esta carencia de perfiles afectó especialmente durante los procesos de validación de los resultados encontrados en la literatura. Aunque se conformó un panel de expertos lo más representativo posible, encontrar participantes con dominio en las diferentes áreas resultó un desafío.

Finalmente, en el estudio de caso del último artículo, se reconoce que el tamaño muestral fue reducido (dos empresas) y que responde a la lógica de un método de investigación intensivo y no extensivo. Si bien este enfoque permitió una exploración profunda y un análisis contextual detallado de las barreras y percepciones en entornos empresariales, inherentemente limita la generalización de los resultados a una población más amplia.

A pesar de estas limitaciones, es importante destacar que se trató de implementar diversas estrategias para mitigarlas, como la triangulación de fuentes de datos, la selección de expertos y el uso combinado de metodologías.

3.4. Futuras líneas de investigación

Los resultados alcanzados abren múltiples vías para la continuidad y expansión de investigación.

En primer lugar, avanzar en la comprensión de la interconexión entre los pilares de la I5.0 y el LSS. Los esfuerzos de investigación deberían concentrarse en identificar las estrategias más efectivas para fusionar I5.0 y LSS, maximizando su potencial sinérgico. Esto incluye el desarrollo de hojas de ruta personalizadas para implementar la metodología LSS en el contexto de la I5.0, adaptándolas a las características concretas de las organizaciones y abordando los obstáculos para alcanzar una transición fluida.

En segundo lugar, profundizar en la evaluación de la I5.0. El modelo propuesto puede ampliarse a partir de la asignación de métricas cuantificables a cada dimensión y desarrollando una puntuación global al conjunto de la organización. Asimismo, proponemos evaluar el impacto a largo plazo de la I5.0 a través de estudios longitudinales. Estos estudios ofrecerían información valiosa sobre los efectos sostenidos de la adopción de la I5.0, particularmente en la colaboración humano-máquina, el desarrollo de habilidades de los trabajadores y los cambios en la cultura organizacional a lo largo del tiempo.

El benchmarking de mejores prácticas entre diferentes industrias y regiones geográficas es otra dirección esencial para fomentar una transición exitosa.

Los marcos regulatorios y los estudios sobre el cumplimiento normativo representarán un área crucial de investigación. Explorar cómo los sistemas legales y regulatorios influyen en la interacción entre los sistemas sociales y tecnológicos brindarían información para garantizar el cumplimiento normativo y fomentar la innovación.

Por último, futuras investigaciones deberían explorar estudios de caso adicionales en diferentes industrias y contextos geográficos.

Con todo, en el actual contexto global caracterizado por crisis ecológicas, disrupciones tecnológicas y transformaciones laborales, la I5.0 surge como una propuesta transformadora para redefinir el papel de la industria en la sociedad. Esta tesis contribuye al desarrollo de dicha visión proponiendo una vía de implementación realista, articulada en torno a la integración con metodologías existentes como el LSS. De este modo, aporta información y herramientas a la necesidad urgente de construir un modelo industrial más sostenible, humano, resiliente, y alineado con los valores de una sociedad que ya no demanda solo crecimiento económico, sino también prosperidad compartida, dignidad en el trabajo y respeto por el planeta.

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5. ANEXO.

COPIA DE LAS SEPARATAS DE LOS ARTÍCULOS.

Industry 5.0's pillars and Lean Six Sigma: mapping the current interrelationship and future research directions

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Abstract

Purpose – In the evolving landscape of Industry 5.0 (I5.0), which emphasises sustainability, human-centricity and resilience, mapping the current interrelationship and future research directions, 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 (SLR), bibliographic network analysis (BNA) and expert validation (EV), 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/value – 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

Paper type 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

The authors wish to express their sincere gratitude to the experts for their valuable contributions in refining the research findings and ensuring their resonance and relevance.

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?

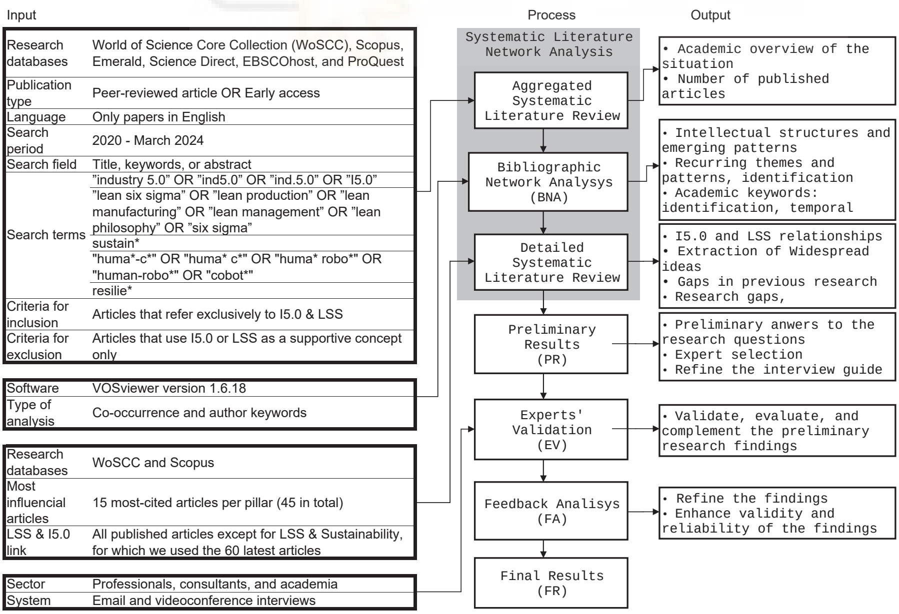
RQ6. How does LSS foster human-centricity in alignment with I5.0?

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 1 summarises the research protocol, including the inputs, process and outputs.

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



Source(s): Authors' own work

Table 1.
Research protocol flowchart

of published articles, facilitated evaluation of the field's stage of maturity and contributed to the initial identification of unanswered research questions (Kraus *et al.*, 2020).

We used *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; Endo *et al.*, 2014). To answer the research questions, we analysed all published articles linking I5.0 to LSS except those on LSS and sustainability, for which we reviewed only the 60 latest articles. We included both *Web of Science Core Collection (*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 min 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 (SLNA), 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 2 summarises the findings.

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.

4.1 Sustainability and LSS

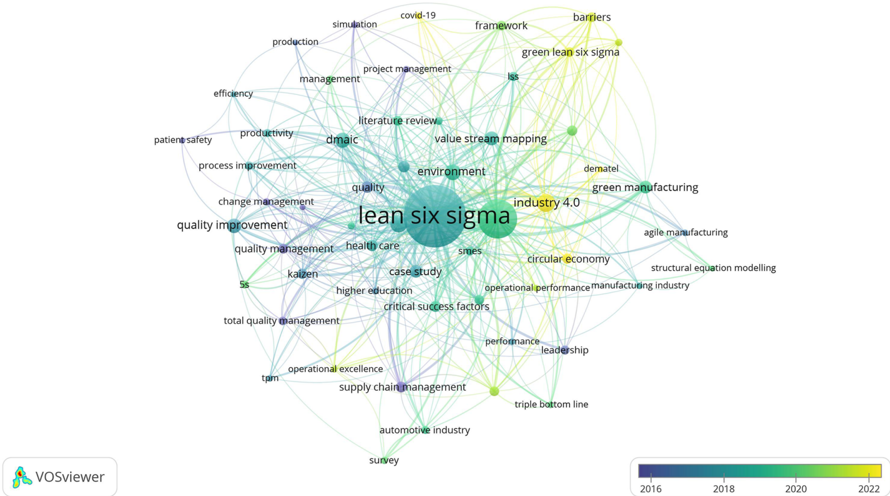
The literature review identified a total of 1,620 articles on this relationship (851 articles common to both databases, 594 found only in Scopus and 175 found only in WoSCC). Analysis of the 15 most-cited articles on the intersection of LSS practices with sustainability objectives yielded valuable insights into the interrelation between these two paradigms.

The BNA (Figure 1) revealed a robust linkage between LSS and sustainability, with a value of 1,591. 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

	WoS	Scopus	Emerald	ScienceDirect	EBSCOhost	ProQuest
Industry 5.0	652	744	307	240	303	356
LSS	8,192	9,673	465	1,849	4,322	6,868
LSS and Industry 5.0	9	12	1	1	1	3
LSS and sustainable	1,009	1,445	110	276	553	651
LSS and human-centric	46	66	20	11	19	8
LSS and resilient	71	63	14	23	30	39

Source(s): Authors' own work

Table 2.
Number of articles



Source(s): Authors' own work

Figure 1.
Bibliographic network analysis – sustainability and LSS

research trend shifting towards emerging concepts such as Industry 4.0, circular economy, green LSS and operational excellence.

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 the potential to reduce waste and pollution. Cherrafi *et al.* (2017) and Piercy and Rich (2015) extended knowledge of the broad 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 PR related to RQ5. These results will be presented in the results section.

4.2 Human-centrism and 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 7 interconnected clusters. These clusters indicate a multi-dimensional 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.

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

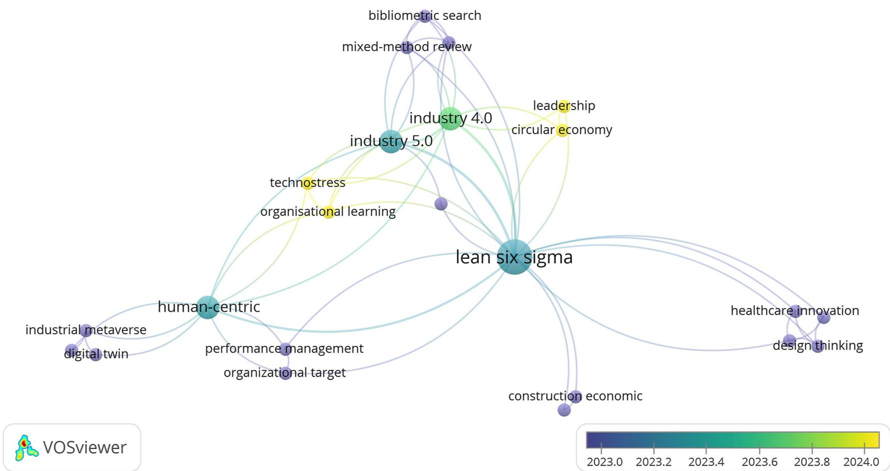


Figure 2.
Bibliographic network analysis – human-centrism and LSS

Source(s): Authors' own work

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.

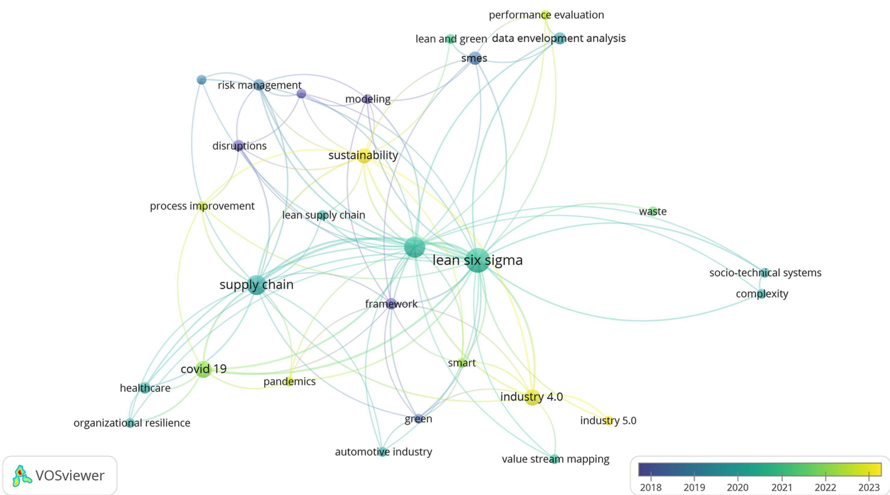
This analysis yielded the PR to RQ6.

4.3 Resilience and 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 8 clusters.

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.



Source(s): Authors' own work

Figure 3.
Bibliographic network analysis – resilience and LSS

This analysis provided the basis for the PR 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. Expert 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 EV 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 was 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 key performance indicators (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 foundation 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 1,794 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). Also, both paradigms 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 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 is that regulatory frameworks are involved: 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: while LSS supports resource conservation (Boopathi, 2024), 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 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 influence 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).

7.1 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.

7.2 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.

8.1 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.

8.2 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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Full Length Article

Assessment model for Industry 5.0: A holistic approach to readiness and integration

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ABSTRACT

Purpose: This study proposes a novel assessment model tailored to the unique requirements of Industry 5.0 transformation utilizing Socio-Technical Theory as a framework. The model seeks to give organizations actionable insights into navigating the complex socio-technical dynamics of I5.0, evaluating organizational readiness holistically, and guiding their transition to this new industrial paradigm across different perspectives and dimensions. By fostering this holistic approach to Industry 5.0 adoption, our study aims to impact industry, society, and institutions significantly.
Methodology: The model was developed using a two-phase research approach. The first phase involved a detailed systematic literature review and a systematic literature network analysis to identify the perspectives, critical dimensions, and guiding questions for the assessment based on Socio-Technical Theory. The second phase refined the preliminary model through expert feedback from industry specialists.
Findings: Our research proposed an assessment model for Industry 5.0, confirmed Socio-Technical Theory as a substantive framework, and identified four core perspectives: strategy, sustainability, human-centricity, and resilience. These perspectives encompass 25 critical dimensions, which were further analyzed through 64 guiding questions. Expert feedback validated the need for the model and highlighted its potential for application from both a strategic and a tactical perspective.
Originality: This study addresses a crucial gap in the literature by presenting a novel assessment model tailored to the unique challenges and opportunities presented by this emerging industrial paradigm. The model's emphasis on holistic readiness and the integration of business strategies goes beyond conventional approaches by fostering a more nuanced understanding of the socio-technical dynamics shaping the future of industry and society. By applying Socio-Technical Theory (STT), this study provides a more comprehensive understanding of the socio-technical dynamics underlying I5.0 transformation. This innovative approach provides organizations with actionable insights into navigating the intricate interplay between advanced technologies, human factors, sustainability principles, and resilience strategies in complex situations, thus advancing both theoretical and practical knowledge in the field of Industry 5.0.

1. Introduction

Industry 1.0 revolutionized human progress with the Steam Age. Industry 2.0 ushered in the Electric Age. Industry 3.0 transformed society with the rise of the Internet and advances in information technology [1].

Introduced in 2011 [2], Industry 4.0 is based on the connectivity of the virtual and real worlds to achieve better results in production with maximum profit [3]. This focus on production results and profit could have adverse effects, such as relegating sustainability to second place, subordinating workers to automatization, or placing insufficient emphasis on social adaptability and resilience. While this focus on production efficiency and profit has driven significant technological advances, it could also have limitations, such as subordination of sustainability, marginalization of workers to prioritize automation, and insufficient emphasis on social adaptability and resilience.

As Industry 4.0 continues to transform manufacturing through advanced technologies, a new industrial paradigm, Industry 5.0 (I5.0), is emerging on the horizon [4]. I5.0 builds on the foundations of Industry 4.0 by prioritizing research and innovation to drive a shift towards a

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sustainable, human-centered, and resilient industrial landscape. It shifts the focus from shareholder value to stakeholder value, aiming to leverage new technologies to foster prosperity that goes beyond jobs and economic growth. This approach respects environmental limits and places the well-being of workers at the heart of the production process [5].

Socio-Technical Theory (STT), developed by Trist [6], offers a robust theoretical framework for understanding the interplay between humans and technologies that I5.0 represents.

In this context, assessments emerge as indispensable tools to guide organizations through the complexities inherent in the transition. These assessments support companies in grasping the extent of modernization required for I5.0 [7], identifying key enablers for a successful transition [8], and classifying their current readiness level to facilitate effective adaptation planning [3]. They also allow organizations to evaluate their I5.0 maturity and align their strategic objectives accordingly [9].

Despite the growing interest in I5.0, the academic and industrial communities face a critical challenge: the lack of robust assessment frameworks tailored to its unique principles. While several models for Industry 4.0 readiness and maturity exist, these models focus predominantly on technological advances and digital transformation, often overlooking the critical interplay between social, human, and environmental dimensions and thus limiting their applicability in the context of I5.0 transformations.

This study arises from the pressing need to bridge this gap. As organizations strive to integrate I5.0 principles into their operations, the demand for a structured, comprehensive assessment model is increasingly recognized as indispensable. The Discussion section presents a detailed state-of-the-art review of existing models, their limitations, and potential adaptations for I5.0.

The remainder of the paper is structured as follows: Section 2 presents STT as a framework for I5.0 and outlines the research questions. Section 3 details the methodology. Section 4 presents the bibliographic network. Section 5 reviews the relevant literature. Section 6 summarizes expert feedback. Section 7 presents the assessment model. Section 8 discusses the study's contributions and constraints.

2. Socio-technical theory as framework

Several theoretical frameworks were considered for this study. Although Contingency Theory argues that organizations must adapt to the different contexts in which they operate [10], it does not address the transformative nature of human-machine collaboration. Actor-Network Theory provides valuable insights into the interactions between humans and non-human entities [11] but does not differentiate between human and non-human actors and lacks the socio-technical integration required for holistic I5.0 assessment. Complex Systems Integration provides a broad perspective on organizational complexity [12] but does not consider the interdependence of social and technical subsystems sufficiently.

STT, in contrast, is uniquely positioned to address these gaps. Its foundational principle of joint optimization aligns with I5.0's emphasis on integrating sustainability, human-centricity, and resilience into technical systems. We thus believe that STT is the most appropriate theoretical lens for creating the assessment model.

Developed by researchers at the Tavistock Institute in the 1950s, STT posits that, for a system to function optimally, balance must be achieved between its social and technical components [13]. Changes in one domain (e.g., technology) will invariably affect the other (e.g., human work processes), and only co-optimization can achieve long-term success. This holistic approach helps mitigate the unintended consequences of purely technology-focused implementation.

STT serves as a key framework to analyze how technological innovations and human factors are integrated within industrial systems. STT highlights the interconnectedness of social and technological subsystems, aiming to optimize overall performance [6]. It also promotes a balanced approach to industrial development, ensuring that technological advances are not pursued at the cost of social factors [13]. Further, STT provides a structured framework for examining emerging challenges with interconnected social and technical dimensions by adhering to its core principles of compatibility, minimal critical specification, the socio-technical criterion, and multifunctionality [14,15].

I5.0 embodies the next phase of industrial transformation, prioritizing a human-centered approach to address the overlooked negative effects of the technology-driven focus of Industry 4.0 [16]. In this context, the long-established STT framework supports the theoretical development of I5.0.

From a practical standpoint, any attempt to drive organizational change must be approached from a socio-technical perspective [13]. An assessment model that integrates STT principles will go beyond technical efficiency to evaluate I5.0′s potential to become a resilient provider of prosperity by ensuring that production respects planetary boundaries and places the well-being of industry workers at the center of the production process [5].

This study advances the following research questions to address academic knowledge and provide practical insights for businesses navigating this transition:

RQ1: Does STT serve as a substantive framework for I5.0?

RQ2: What perspectives frame effective assessment of I5.0?

RQ3: What dimensions of each perspective must organizations assess to embrace I5.0?

3. Methodology

This study utilized a two-phase approach to develop the I5.0 assessment model to ensure its relevance within the STT framework. The literature review provided a solid foundation, and expert feedback improved the model's validity and practical application. Data extraction followed the protocol presented in Table 1.

The initial phase integrated Systematic Literature Review methodology with quantitative Bibliographic Network Analysis, using contemporary bibliometric tools to identify emerging themes and trace their development over time [17]. This approach was considered appropriate for the study's interdisciplinary scope and focus on emerging topics, as highlighted by Ejsmont et al [18]. The review followed the guidelines established by Tranfield et al [19].

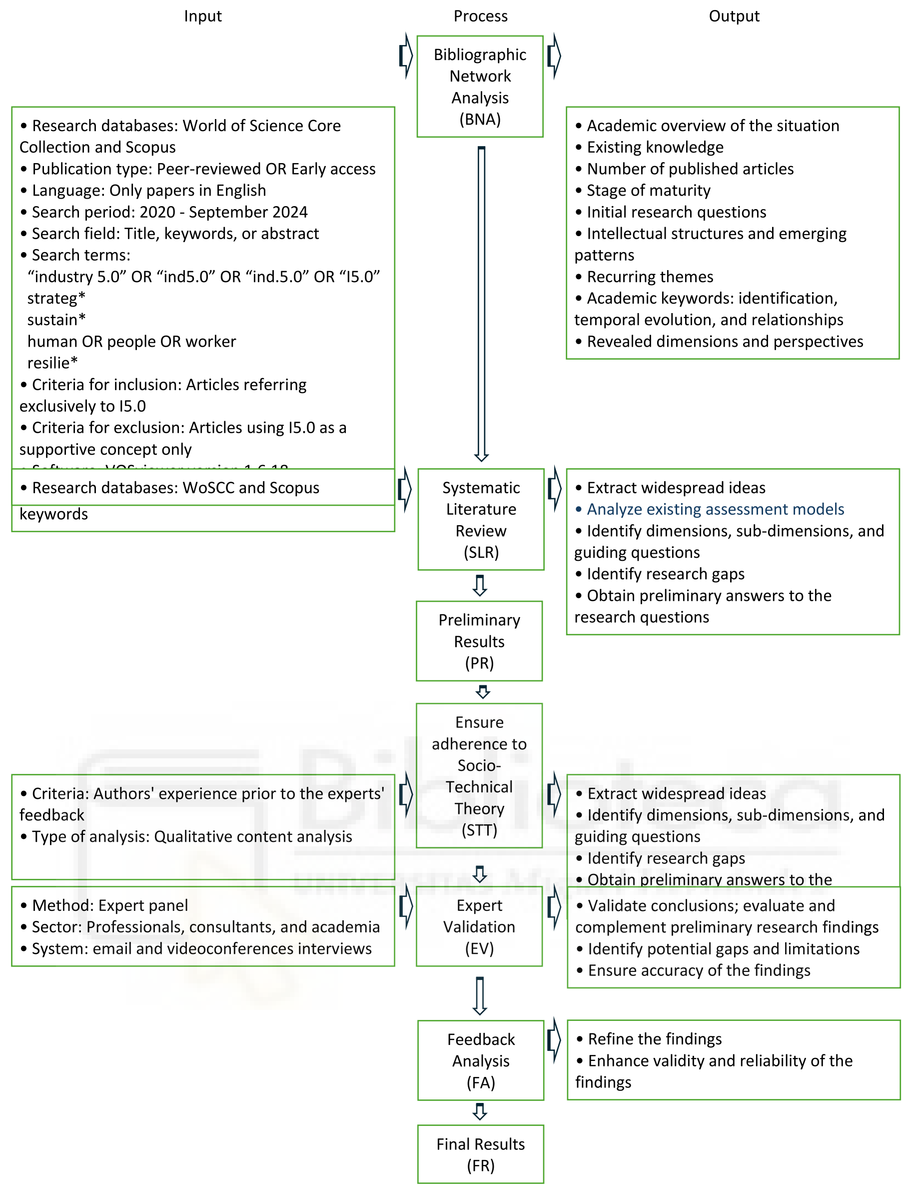
I5.0 can be assessed through four primary perspectives, which encompass its three core pillars (human-centricity, sustainability, and resilience). Because these pillars are grounded in interconnected core values, we introduced an additional overarching perspective to integrate and align the commonalities between them, such as resource allocation and strategic alignment.

From the Corporate Social Responsibility (CSR) perspective [20], key factors to consider in the management of organizations are the natural environment and the social aspect, as they address the demands of key stakeholders [21]. According to the I5.0 literature [3,5], the framework of dimensions proposed contains these two factors. The natural environment is included in the concept of sustainability, and social considerations are addressed mainly in the human-centric perspective.

Several validated frameworks and indices support the idea of using multiple perspectives for assessment. For instance, Corporate Sustainability Assessment (CSA) links sustainability with business strategies [22]. The Influential Network Relationship Map (INRM) helps analyze and evaluate the complex interrelationships of development factors [23]. The Balanced Scorecard (BSC) aligns strategic objectives across diverse domains [24]. Finally, Grey Influence Analysis (GINA) studies the causal relationships among factors [25]. These frameworks informed the design of our assessment model to ensure a comprehensive, integrated approach to evaluating I5.0 readiness.

Bibliographic Network Analysis enabled the authors to obtain an academic overview of the situation, intellectual structures, emerging patterns, and temporal evolution of the perspectives. It also revealed the

Table 1
Research protocol flowchart. Source: developed by the authors.



Source: Developed by the authors.

dimensions or critical factors that define each perspective, thus elucidating the knowledge constituents [26]. The analysis was performed using VOSviewer v1.6.18 software and bibliographic coupling technique to identify the interconnections among authors' keywords [27]. Researchers widely recognize this tool as a standard approach in literature reviews [28] to highlight emerging themes and trends related to the socio-technical nature of I5.0.

The search period included publications from the start of 2020—commonly acknowledged as the inauguration of I5.0 [29] to September of 2024.

The Systematic Literature Review identified, classified, and summarized competencies relevant to I5.0 [30]. The literature review of 260 articles on assessments identified the fundamental dimensions and sub-dimensions, and enabled formulation of the guiding questions grounding evaluation of organizations' journey. Table 2 summarizes the dimensions and sub-dimensions extracted and provides references for each sub-dimension, as recommended by Amaral and Peças [31].

The results obtained from the Systematic Literature Review were analyzed within the framework of STT's principles of compatibility (harmonious interaction between social and technical systems), minimal critical specification (only essential aspects are specified), socio-technical criterion (optimizing social and technical systems for sustainability, human-centricity, and resilience), and multifunctionality (promoting diverse skills and employee engagement). Finally, Table 3 details insights from the analysis that formed the basis for the preliminary assessment model.

The second phase involved refining and validating the preliminary model to assess its relevance, clarity, and appropriateness [32]. This phase was performed with a panel of experts who provided feedback via email and video conferences [33].

Following common practice (e.g., [34]), the panel of experts was selected based on two characteristics: extensive familiarity with I5.0,

Table 2
Dimensions and sub-dimensions.

Perspective	Dimensions	Sub-dimensions	References
Overarching	vision and strategy	roadmap	[40]
		stakeholders	[41]
		indicators	[42]
	resource allocation	investments	[43]
	innovation	culture	[44]
		framework	[45]
	communication	efficient communication	[46]
		organization reputation	[47]
	technological readiness	technological infrastructure	[48]
		integration with existing systems	[9]
		limitations to I5.0 implementation	[49]
	data and analytics	data management	[50]
Sustainability	resource efficiency	resource consumption	[51]
		energy	[52]
		material waste	[53]
	circular economy	design	[54]
		life cycle	[55]
		environmental impact	[56]
	renewable energy	renewable sources	[57]
		energy distribution	[58]
	eco-friendly materials	footprint - ecosystems	[59]
	green supply chain	transparency and collaboration	[60]
		sustainable sourcing practices	[61]
Human-centrism	human-machine collaboration	integration	[62]
		automation	[63]
		efficiency	[64]
		worker experience	[65]
	skill development and training	digital literacy	[66]
		expertise	[67]
		learning platforms	[68]
		upskilling and reskilling	[69]
	safety and ergonomics	safety and wellbeing	[70]
		ergonomic improvements	[71]
		user-friendly	[72]
		safe working environment	[73]
	work-life balance	remote work	[74]
		flexible scheduling	[75]
		prevent technology-related burnout	[76]
	personalization of work experience	worker preferences and needs	[77]
		feedback from employees	[78]
	ethical considerations	ethical concerns	[79]
		data privacy	[80]
		algorithmic bias	[81]
		safeguards	[82]
		unethical technology use	[83]
Resilience	cybersecurity	security and privacy of data	[84]
		vulnerabilities	[85]
	adaptive technologies	changing conditions and unexpected disruptions	[60]
		integration of adaptive technologies	[86]
	redundancy and flexibility	adjustments to changes or unexpected events	[87]
	data and analytics	data analytics and AI	[88]
		decision-making	[89]
		real-time decision-making during disruptions	[90]
		employee empowerment	[91]
	supply chain resilience	vulnerabilities	[43]
		risk management	[92]
		collaboration with partners	[93]
	remote operations	disruptions	[94]
		teamwork in remote work scenarios	[95]
		simulations reflect the real world	[96]

Source: Developed by the authors.

and managerial and operational experience. These criteria ensured valuable insights into the paradigm's practical implementation [35]. A total of 12 specialists from six different fields were interviewed to achieve a broad array of perspectives: technology centers (2), industrial clusters (1), I5.0 initiatives (5), consultancies (2), business parks (1), and business schools (1). This sample size is common practice in the early stages of research [36]. Similar approaches have been used in numerous prior studies, such as Dybå [37], who engaged 11 experts for a similar review.

Insights from these consultations were derived from semi-structed interviews to validate conclusions from the literature review, evaluate and complement the preliminary research findings, identify potential gaps and limitations, and enhance theoretical rigor through the STT lens. Following Dieste et al [38], the authors reviewed the results of the feedback collectively to determine the final model.

While pilot testing was beyond the scope of our research, the interdisciplinary and iterative approach ensured that the final I5.0 assessment model was grounded in both authoritative literature and expert insights.

4. Bibliographic network analysis

The content-focused literature revealed a diverse spectrum of relevant domains and concepts, equipping organizations with tools to navigate the dynamic I5.0 landscape effectively. The following sections summarize the findings.

4.1. Overarching

A bibliometric analysis of 404 documents in the strategy domain revealed an intricate network of researchers' keywords. Keywords such as advanced technologies, collaborative intelligence, culture, cyber-physical systems, disruptive technologies, energy efficiency, ethics, innovation ecosystems, leadership, ontology, resource allocation, Supply Chain 5.0, and University 5.0 formed seven distinct clusters. These clusters showed 178 interconnections, with a cumulative link strength of 636. The timeline analysis highlighted emerging concepts such as digital transformation, circular economy, lean management, smart manufacturing, blockchain, digital twins, and human-machine integration (Fig. 1).

4.2. Sustainability

Exploring the scientific landscape of sustainability revealed 916 articles with keywords such as bioeconomy, bioenergy, digital circular economy, digital green innovation, energy efficiency, environmental sustainability, green finance, green manufacturing, innovation ecosystems, renewable energy, social sustainability, sustainability performance, and waste management. These terms converged into four clusters, forming a web of 201 interconnections with a cumulative link strength of 1831.

The analysis also pointed to emerging research trends, focusing on concepts such as sustainable development goals, circular economy, smart manufacturing, human-machine integration, machine learning, digital transformation, and digital twins (Fig. 2).

Table 3
Assessment model and guiding questions.

Overarching perspective
1. Vision and strategy
1.1. The organization has a defined strategy to integrate the principles and technologies of I5.0.
1.2. The sectors involved (employees, customers, and suppliers) have helped shape and support this vision and strategy.
1.3. The strategic objectives of the organization are harmonized with the core principles of the I5.0 vision.
2. Resource allocation
2.1. Adequate resources (financial, human, and technological) have been allocated to support initiatives covering all three pillars.
2.2. The organization has the right balance of investments in sustainability, human-centered, and resilience initiatives.
3. Innovation framework
3.1. The organizational culture fosters an enabling environment to analyze and implement innovative solutions aligned with the three pillars.
3.2. Examples of innovations resulting from the convergence of sustainability, human-centered, and resilience efforts can be provided.
4. Communication strategy
4.1. Global visions and commitment were communicated effectively to internal and external stakeholders.
4.2. Tangible examples can be provided where communication of the implementation of these pillars significantly influenced the organization's reputation.
5. Technological preparation
5.1. A comprehensive assessment of the organization's existing technological infrastructure (hardware, software, and communication systems) has been conducted.
5.2. Existing systems are well integrated with I5.0 technologies (such as Artificial Intelligence, Internet of Things, or Robotics).
5.3. The main limitations hindering the organization from incorporating new technologies have been identified.
6. Data strategy
6.1. The organization is equipped with robust data management capabilities spanning collection, storage, processing, and analysis.
6.2. Available data are leveraged effectively by their transformation into actionable information.
6.3. Decision-making within the organization is primarily data driven.
Sustainability perspective
7. Resource efficiency
7.1. New technologies, such as IoT and data analysis, have been implemented to facilitate real-time optimization of resource consumption.
7.2. The company utilizes technologies to improve energy distribution and efficiency.
7.3. There is monitoring and communication of material waste reduction in production operations.
8. Circular economy
8.1. Product design aligns with the principles of reduction, reuse, and recyclability.
8.2. Product design focuses deliberately on extending products' life cycle.
8.3. A detailed analysis of the product life cycle has been performed, and it covers purchases, delivery to customers, and end of their useful life.
8.4. Life cycle assessments are conducted to identify and address the product's environmental impact.
9. Integration of renewable energies
9.1. Indicators are used to track total energy consumption of the installation sourced from renewable sources.
9.2. The feasibility of implementing renewable energy sources has been thoroughly explored and evaluated.
9.3. Analyses have been conducted to assess the potential for implementing renewable energy distribution systems.
10. Eco-friendly materials
10.1. Indicators track the percentage of products incorporating sustainable and ecological materials.
10.2. The impact of these materials on reducing the ecological footprint is quantified.
10.3. Ongoing efforts are made to source and integrate ecological materials.
11. Supply chain
11.1. Continuous efforts are made to uphold sustainable sourcing practices throughout the supply chain.
11.2. Comprehensive mechanisms and protocols are in place to monitor and assess the social and environmental impact of supply chain operations continually.
12. Social
12.1. Stakeholders' needs are identified, and plans for meeting their demands are established and managed.
12.2. Equity and diversity within human resources are planned and managed.
12.3. The work climate is planned, measured, and managed.
Human-centricity perspective
13. Collaboration between people and machines
13.1. The integration of workers with machines is evaluated, with a focus on improving productivity and safety.
13.2. Collaboration systems between people and robots have been implemented in production processes.
13.3. Concrete examples can be provided where people and machines collaborate seamlessly, improving both efficiency and the worker's experience.
14. Skills development and training
14.1. The readiness of the workforce to adapt to I5.0 has been assessed, covering factors such as digital literacy and willingness to adopt new technologies.
14.2. Systems are in place to detect workforce training and retraining needs to align with the changing technology landscape.
14.3. Steps are taken to prioritize training and retraining initiatives to align the workforce with the ever-evolving technology landscape.
15. Safety and ergonomics
15.1. Processes exist that focus on integrating technology into the workplace to improve workers' safety and general well-being.
15.2. Concrete examples of ergonomic improvements facilitated by the adoption of technology can be provided.
15.3. Measures have been implemented to ensure that technological interfaces are user-friendly and promote a safe working environment.
16. Work-life balance
16.1. The technological solutions adopted evaluate and contribute to employees' work-life balance.
16.2. Cases can be identified where technology has enabled remote work or flexible schedules, improving work-life balance.
16.3. Proactive measures are taken to mitigate technology-related burnout and maintain employee well-being.
17. Personalization of work experience
17.1. Technologies within the organization are adapted to meet workers' individual preferences and needs.
17.2. Employee feedback is collected and used to refine and improve personalized work experiences.
18. Ethical considerations
18.1. The organization has a defined system to address ethical concerns related to technology, such as data privacy or algorithmic bias.
18.2. Proactive safeguards against unethical use of technology are in place.
18.3. Employees are actively engaged in issues related to the ethical implementation of technology in their workplace.
Resilient perspective
19. Safety
19.1. Rigorous measures are evaluated and maintained to safeguard the security and privacy of data and interconnected systems.
19.2. Methodologies are in place to proactively identify possible vulnerabilities and weaknesses in the organization's cybersecurity measures.

(*continued on next page*)

Table 3 (*continued*)

Overarching perspective
20. Adaptive technologies
20.1. Technology systems respond dynamically to changing conditions and unforeseen disruptions.
20.2. Adaptive technologies are seamlessly integrated into the organization's strategy.
21. Redundancy and flexibility
21.1. Redundancy measures in critical processes are effectively intertwined, ensuring seamless continuity in the face of potential disruptions.
21.2. Technological systems automatically make quick adjustments to adapt to changes in demand or unforeseen events.
22. Data-driven decision making
22.1. The extent to which the organization relies on data analytics and artificial intelligence for real-time decision-making during potential disruptions has been assessed.
22.2. Employees are empowered to leverage available data to facilitate resilient decision-making.
23. Supply chain resilience
23.1. Vulnerabilities in the supply chain are regularly monitored and assessed to enable proactive risk management.
23.2. The organization has developed mechanisms to engage collaboratively with stakeholders to strengthen supply chain resilience through technology solutions.
24. Remote operations and collaboration
24.1. A system is available for operations to transition smoothly to remote modes during possible interruptions.
24.2. There is a system in place to integrate communication and collaboration tools to maintain effective teamwork for remote work.
25. Scenario planning and simulation
25.1. Technology is used for scenario planning and simulation of potential disruptions.
25.2. Mechanisms have been put in place to ensure that simulations accurately reflect real-world complexities, facilitating accurate assessment of resilience.

Source: Developed by the authors.

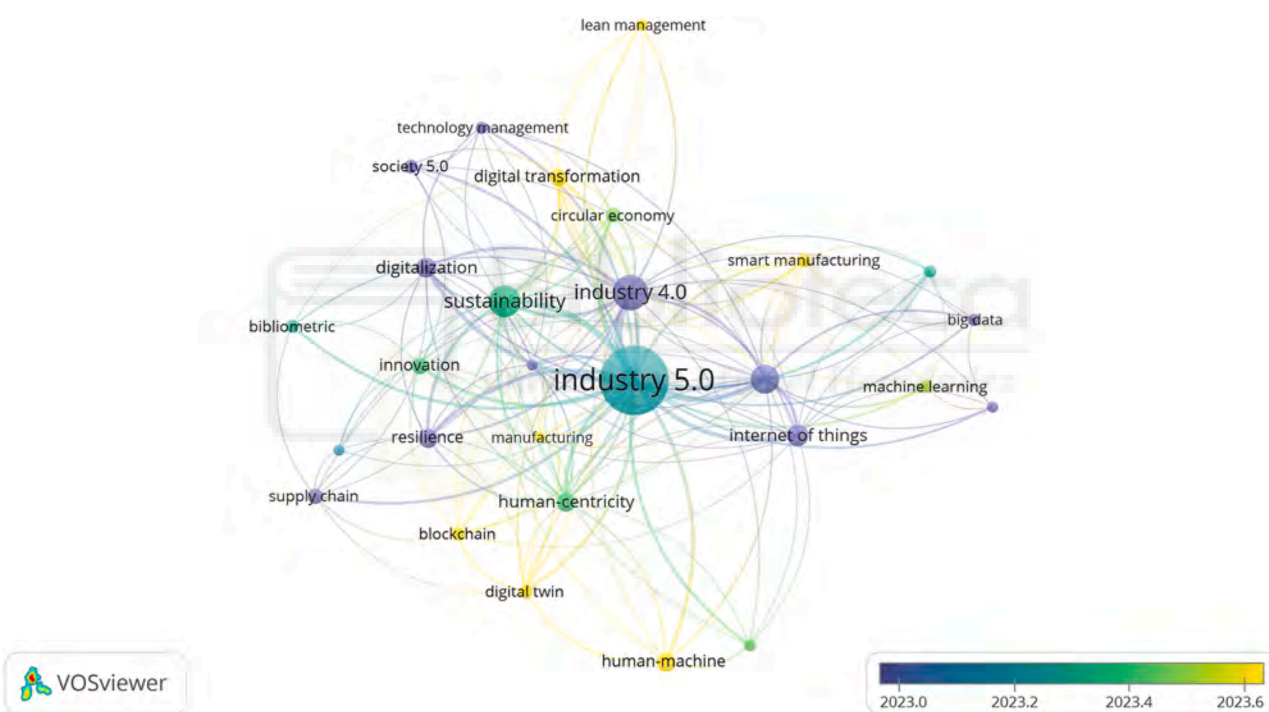


Fig. 1. Bibliographic map: overarching.
Source: Developed by the authors.

4.3. Human-centrism

The review identified a total of 1487 articles that sought to understand the role of employee-centric approaches in the context of organizational improvement initiatives. Keywords in this domain included collaborative robots, human behavior, human factors, human-centric smart manufacturing, knowledge management, Operator 5.0, skills, smart education, and training.

These terms suggest a multidimensional approach to organizational improvement, emphasizing employee-centric practices. They formed five clusters with 225 interconnections, illuminating a network of in-depth knowledge with a cumulative link strength of 1532. Lastly, research trends are shifting toward concepts such as ergonomics, the metaverse, cyber-physical systems, and information systems (Fig. 3).

4.4. Resilience

The review identified 391 articles in the domain of resilience. Researchers used 1128 keywords related to concepts such as supply chain resilience, cybersecurity, manufacturing resilience, adaptability, resilient industries, risk management, and resilient supply chains. These terms formed four clusters with 154 interconnections, demonstrating their connectedness with a cumulative link strength of 675. The analysis also indicated a shift in research trends toward concepts such as sustainable manufacturing, digital transformation, and human-centric manufacturing (Fig. 4).

5. Systematic literature review

This section synthesizes key academic insights, examining I5.0 through the lenses of strategy, sustainability, human-centricity, and

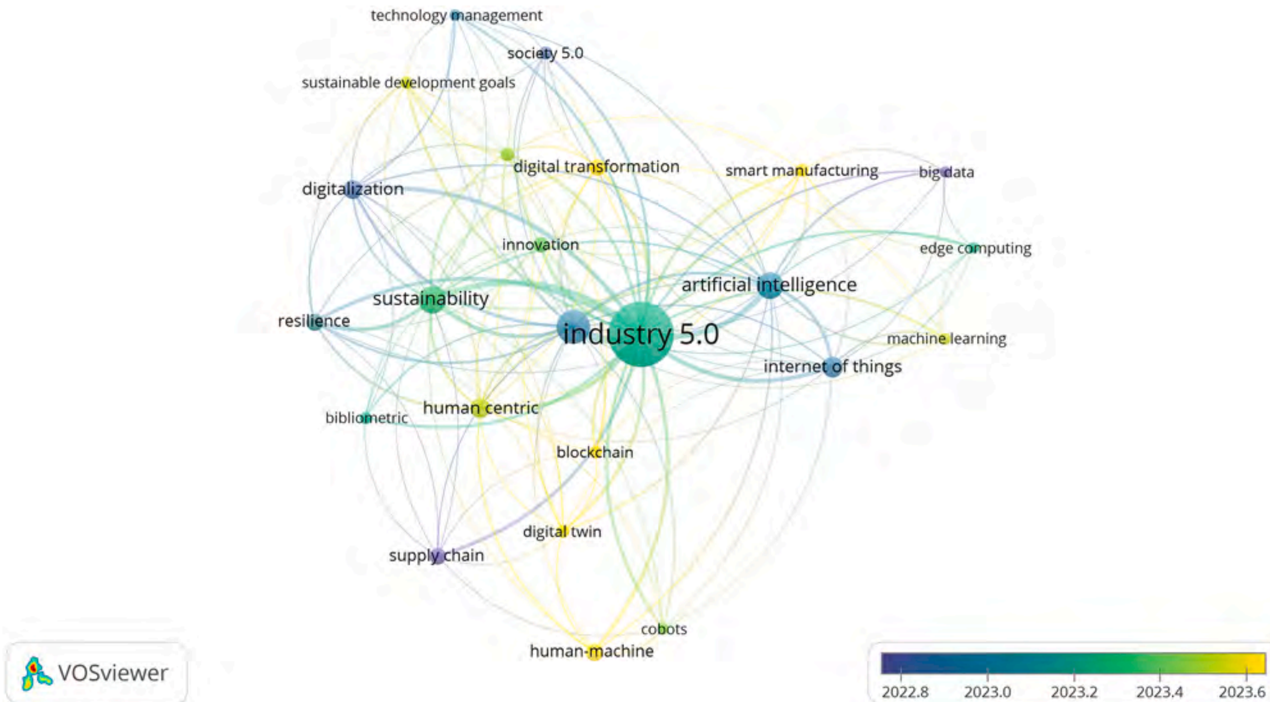


Fig. 2. Bibliographic map: sustainability.
Source: Developed by the authors.

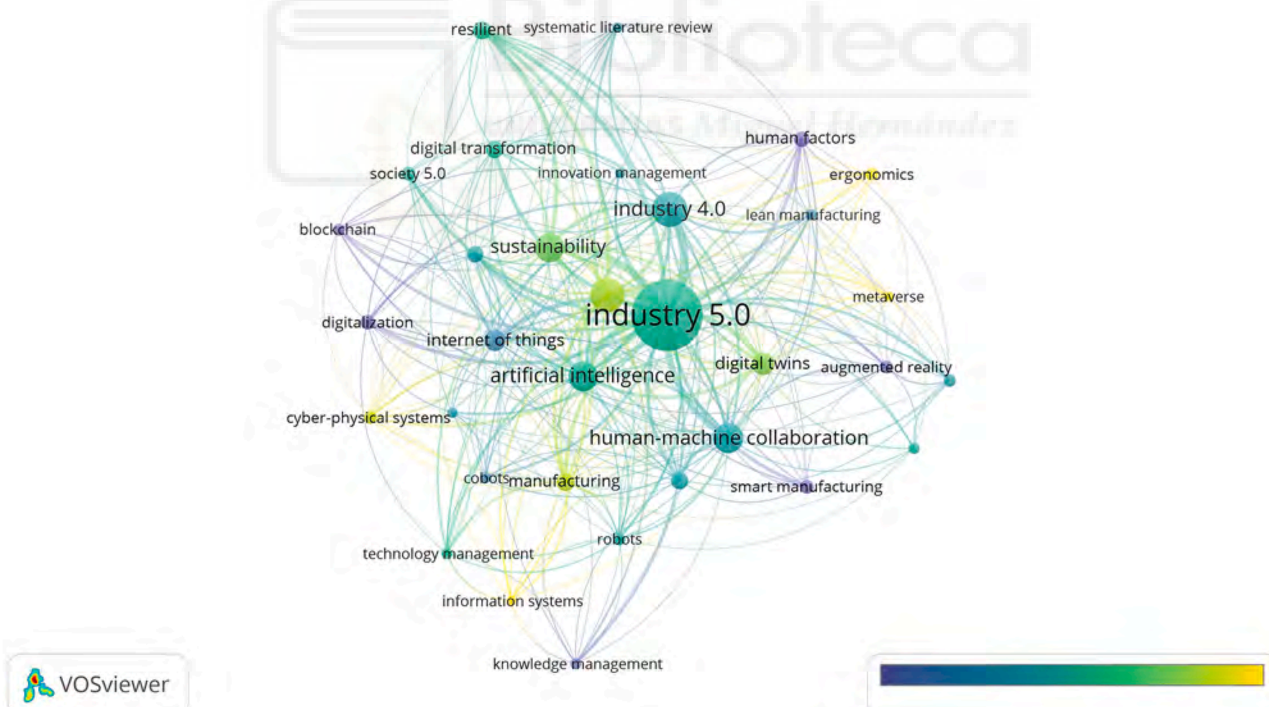


Fig. 3. Bibliographic map: human-centrism.
Source: Developed by the authors.

resilience. It identifies and categorizes the dimensions and sub-dimensions grounding these themes, as presented in Table 2. An in-depth analysis of existing assessment models will be conducted in the Discussion section. This analysis serves as the foundation for development of a preliminary assessment model and its corresponding guiding questions.

5.1. Overarching

STT emphasizes a holistic approach to organizational design, aligning with I5.0′s strategic perspective, which calls for a comprehensive plan to integrate technology and I5.0's pillars [39]. An analysis of 75 articles on strategy identified six dimensions and 12 sub-dimensions, providing a framework to guide the strategic direction of I5.0. This

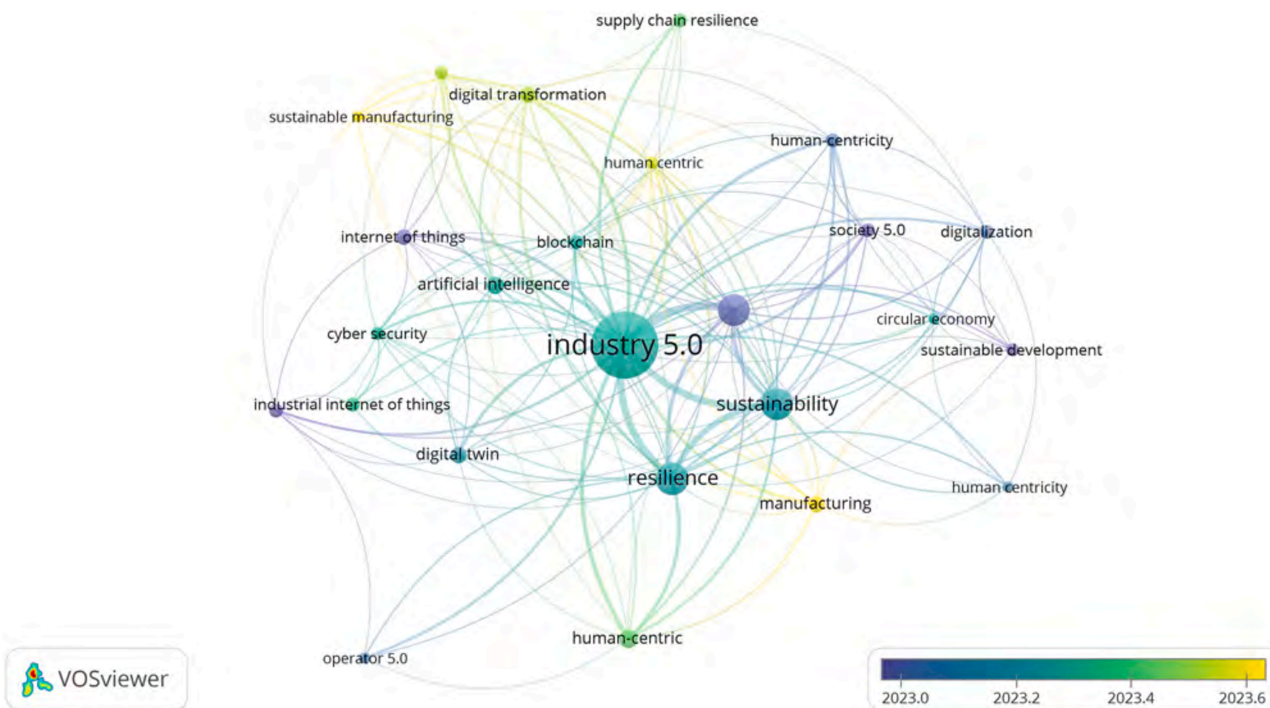


Fig. 4. Bibliographic map: resilience.
Source: Developed by the authors.

compilation focuses on specific references for each concept.

5.2. Sustainability

STT acknowledges the importance of balancing technological advances with environmental considerations. I5.0′s sustainability perspective emphasizes the need for sustainable practices and resource management, which aligns with STT's focus on long-term viability [97]. A review of 167 articles on sustainability revealed five distinct dimensions and 11 sub-dimensions critical to implementing sustainable I5.0 practices.

5.3. Human-centrism

Both STT and Industry 5.0 prioritize the human element in organizational systems. STT emphasizes the importance of considering human needs, motivations, and capabilities. Industry 5.0's human-centric perspective focuses on creating workplaces that empower employees and enhance their well-being [98]. The review of 298 articles on human-centrism identified six key dimensions and 22 sub-dimensions, highlighting the critical role of human-centric practices in I5.0.

5.4. Resilience

STT's focus on adaptability and flexibility aligns with I5.0′s resilience perspective. Both frameworks recognize the importance of being able to respond to changing circumstances and disruptions [99]. An analysis of 82 central articles on resilience identified six dimensions and 15 critical concepts essential for fostering resilience in I5.0.

6. Experts' feedback

The initial assessment model, constructed from academic literature, was critically reviewed by a panel of experts. Their feedback validated the model, emphasizing the importance of having an assessment with a holistic approach. The experts confirmed that the perspectives, dimensions, and guiding questions effectively addressed the industry's needs and showed no signs of redundancy. They also affirmed the model's feasibility for implementation from both strategic and tactical viewpoints.

The experts' feedback also highlighted several areas for improvement. Experts recommended enhancing the model's usability by clarifying specific terminology (e.g., "work climate" and "real-time") to improve comprehension and streamline its structure for a better user experience.

Additional suggestions for future improvements included providing guidance on how to conduct assessments, defining key concepts more clearly, and differentiating between essential and desirable aspects of the assessment.

The experts also proposed incorporating post-assessment procedures, implementing a facilitation program, and integrating benchmarking capabilities.

Lastly, the experts raised concerns about the unique challenges faced by SMEs, particularly their limited resources. They also stressed the importance of adapting the model to various countries' legislative frameworks (e.g., employee consultation constraints in Germany). These valuable insights were incorporated, producing the final version of the assessment model, presented in the following section.

7. Results

This section assesses progress made in answering the research questions and presents the I5.0 assessment model developed by integrating insights from bibliographic network analysis, the literature review, STT, and feedback from industry experts.

RQ1 - STT as Framework: The study provides evidence supporting the use of STT principles as a framework for development of I5.0, integrating both technical and social aspects of this technology. The comparative analysis confirmed that STT provides a more comprehensive framework than Actor-Network Theory, Systems Theory, or Contingency Theory, thus supporting the choice of STT as the foundational theory for this study. The conclusions are further developed by applying our findings to answer the research questions.

RQ2 - I5.0 Perspectives: The analysis identifies four foundational perspectives that ground the assessment model: overarching, sustainability, human-centricity, and resilience. These perspectives form the structural core of the model, ensuring comprehensive evaluation of organizations' readiness for I5.0.

RQ3 – I5.0 Dimensions: The findings establish 25 critical dimensions within these four perspectives, each accompanied by guiding questions. These dimensions enable organizations to evaluate the current state of their I5.0 implementation and address key areas for improvement.

Fig. 5 provides a visual summary of the assessment model, illustrating its key components and enhancing comprehension of its structure.

Table 3 presents the finalized I5.0 assessment model, the key outcome of this study. This model gives organizations a practical tool to assess their maturity in adopting I5.0, identify areas requiring improvement, and pinpoint crucial enablers for a successful transition.

The model also helps organizations align their strategies with current capabilities, resources, and objectives; navigate the complexities of I5.0; and ensure adaptability in a dynamic industrial landscape.

The scoring system should be tailored to the specific goals of the assessment. As a model, we propose the scoring used in the Global Reporting Initiative (GRI), one of the original scoring tools proposed by researchers [100], which has been used for more than two decades as a valid quantitative scoring method in reporting. However, our assessment does not focus only on reporting. We also wish our assessment scale to become a guide for implementation. We therefore adapt the scoring tool [0-4] used by the authors of the GRI for adoption on each guiding question. The lowest score is 0 – "no adoption" and the highest 5 –"your firm is recognized in the industry as a leader in that practice." In sum, we adapt the scale proposed by Morhardt et al. and add the score of 5. Thus, to assess maturity in adopting I5.0, we propose:

0 – Not Initiated: No actions have been taken toward I5.0 adoption.

1 – Exploration Phase: Initial discussions or awareness, but no concrete implementation.

2 – Partial Implementation: Some initiatives are in place, but progress is limited and inconsistent.

3 – Advanced Implementation: Broad adoption across key areas, though some gaps remain.

4 – Fully Integrated: The initiatives are embedded in operations with measurable impact.

5 – Industry Benchmark: Recognized as a leader in I5.0 adoption, establishing best practices for others.

Organizations can benefit from conducting the assessment, which enables them to identify strategic priorities for adoption of I5.0 principles.

8. Discussion

The advent of I5.0 represents a fundamental shift away from traditional industrial practices, reshaping interactions within the quintuple helix innovation framework, which integrates industry, government, academia, the public, and the environment [101]. A significant challenge in the transition to I5.0 is the lack of robust assessment frameworks. As highlighted by Zizic et al. [3], traditional models are not adequately equipped to evaluate the specific requirements and nuances of I5.0, a finding further supported by our literature review.

The assessment model developed in this study builds upon and adapts a range of previous assessment frameworks. For example, Maturity Models in Industry 4.0 such as those proposed by Hajoary et al.

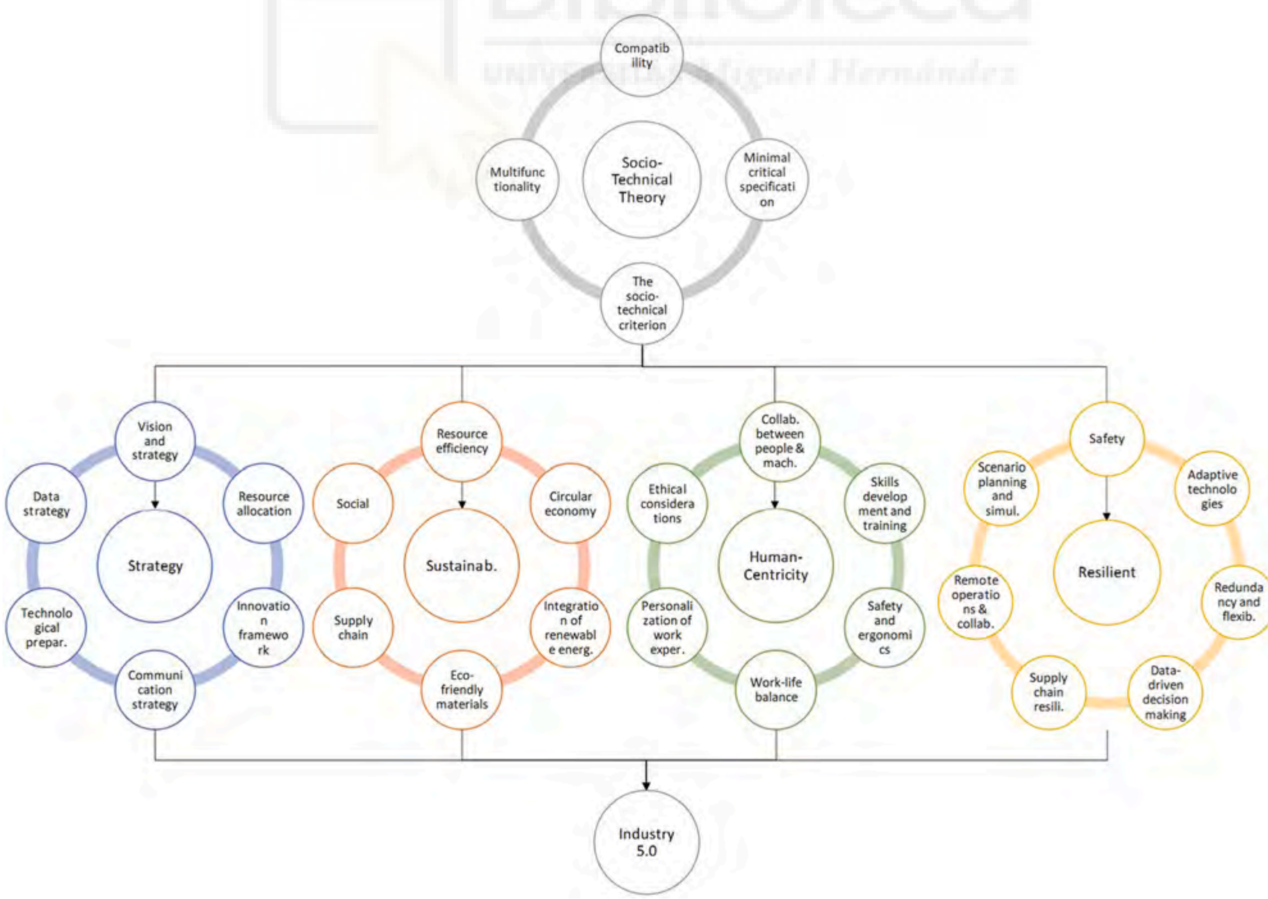


Fig. 5. I5.0 assessment summary diagram.
Source: Developed by the authors.

[[101]] focus on business model transformation, production processes, strategies, and objectives. Santos and Martinho [[102]] present a model for initial diagnosis and establish a roadmap for implementation. These models often define stages of maturity to help organizations identify their current position and outline the actions required to advance. These models tend to be heavily technology-centric, however, often overlooking critical socio-technical dimensions, such as workforce adaptability, human-centricity, and ethical considerations.

Technology Readiness Assessments such as those inspired by Technology Readiness Levels are commonly used to evaluate the development and implementation of new technologies. For example, Olechowski et al. [102] analyzed system complexity, planning and review, and the validity of assessments, whereas Samaranayake et al [103]. prioritized key determinants of Industry 4.0 readiness. While these assessments provide a systematic way to measure the maturity of specific technologies, they often overlook broader organizational readiness and the interplay between human and technical systems.

Sustainability and Circular Economy Models, such as the Corporate Sustainability Assessment, that support businesses transitioning toward addressing sustainability [104], or the Circular Economy Index that which evaluates environmental performance and the adoption of sustainable practices within organizations [105]. These models align with sustainability goals by emphasizing resource optimization, waste reduction, and environmental responsibility. Such models often lack integration with human-centric and resilience-focused dimensions, however, making them insufficient for holistic I5.0 assessment.

National Maturity Models—such as that developed by Bhamriya and Gupta [106], which assesses Industry 4.0 readiness at a national level by considering policy, infrastructure, and economic factors; or Government Maturity Models analysis by Pirannejad and Ingrams [107], which evaluates open government initiatives holistically—provide insights into systemic readiness. These models highlight the role of governmental policies and national strategies. They are less applicable to individual organizations, however, and do not typically account for socio-technical interactions or human-machine collaboration.

Our model is also complemented by studies such as those by Hein-Pensel et al [9]. on general maturity models, Konstantinidis et al [109]. on machine vision, Chakir et al [110]. on web-based attack detection, and Caggiano et al [111], who support transition of production systems; Botti and Baldi [112], who combine Business Model Innovation with I5.0, Madzik et al [113]. on a systematic framework; and Vacchi et al [114]. for process technological sustainability. While these models provide initial insights into how to align technical and social systems, they remain nascent, with limited empirical validation or application to the unique requirements of I5.0, such as enhanced human-machine collaboration and resilience.

This study fills a significant gap by presenting a novel I5.0 assessment model that provides key insights for companies embarking on I5.0 transformation. A key takeaway is the need for holistic integration, ensuring that sustainability, human-centricity, and resilience are embedded in strategic planning rather than treated as supplementary initiatives. By aligning these elements within the organization's strategy, companies can prevent them from being marginalized as optional best practices and instead position them as core drivers of long-term growth and competitiveness. Furthermore, this strategic alignment ensures that corporate objectives remain consistent with the fundamental principles of I5.0, ultimately fostering both business success and positive societal impact [92].

The model also underscores the importance of strategic prioritization, urging organizations to manage the transition from their current paradigm to a new, less certain business approach [31]. This transition demands careful resource allocation and the adoption of data-driven decision-making processes to support the journey [114].

Responsibility for sustainability is a central component of the model, guiding organizations in integrating environmental elements into their operations. Dimensions such as resource efficiency, circular economy, and renewable energy implicitly highlight the economic facet of sustainability. These practices not only strengthen environmental management but also enhance operational efficiency, cost-effectiveness, and overall competitiveness [115]. Moreover, it reinforces the social dimension of the human-centric pillar by fostering job security, workforce well-being, and organizational resilience [116].

In addition, the model emphasizes the creation of a human-centric work environment, focusing on human-machine collaboration, skill development, safety, and work-life balance. These factors are essential for building workplaces that attract and retain talent, while ensuring employee well-being [58] and enfolding technology and humans [117].

Further, the model encourages resilience and adaptability, urging organizations to evaluate their security measures, supply chain resilience, and ability to make data-driven decisions during crises.

Finally, the model promotes resilience and adaptability by encouraging organizations to evaluate their security protocols, strengthen supply chain resilience, and enhance their capacity for real-time, data-driven decision-making during crises [90]. These capabilities are crucial for maintaining operational continuity and long-term viability in an increasingly dynamic and unpredictable industrial landscape.

I5.0 represents a transformative shift in industrial paradigms, moving beyond the automation of Industry 4.0 to emphasize nuanced collaboration between humans and machines [118]. This study addresses a critical gap in I5.0 research by introducing a pioneering assessment model specifically designed for this emerging industrial era, using STT as its foundational framework.

The model synthesizes insights from existing literature, industry expert feedback, and STT to address the lack of a standardized assessment tool for I5.0. It provides a comprehensive framework to guide organizations on their journey toward implementing I5.0 principles. By integrating STT, the model examines how organizational structures, employee skills, and company culture align or potentially clash with new technological advancements. This assessment leads to actionable recommendations for organizational change management, emphasizing leadership, effective communication, and adaptability in response to socio-technical needs.

Alongside sustainable practices, STT is embedded in both technical and social processes. It promotes eco-friendly technologies while also supporting human well-being by minimizing negative impacts on both people and the environment. Technical processes, such as energy efficiency and waste reduction, are aligned with social imperatives, including equitable labor practices and sustainability in the workplace, minimizing negative impacts on both people and the planet.

Furthermore, STT provides a lens through which to evaluate the evolving roles of humans—workers, managers, and consumers— in their interaction with technological systems. It underscores the need to align both human and technical elements for successful implementation. This framework is essential for explaining evolution from the automation-centric focus of Industry 4.0 to the human-machine collaboration central to I5.0 [118]. It ensures that worker satisfaction, job design, and collaboration remain priorities during technological upgrades, fostering a workplace environment that values the human element as much as technological advance.

Finally, an STT approach in I5.0 fosters resilience by ensuring that systems are designed to accommodate human flexibility and creativity. In cases of technological failure, human workers can adapt and reconfigure systems to maintain operational continuity—an advantage over purely automated systems, which may come to a standstill in the event of a failure. The integration of human expertise with I5.0 technologies enhances system resilience and adaptability, minimizing the impact of potential disruptions and maximizing efficiency [99].

8.1. Contribution to theory

This study makes a significant theoretical contribution to the emerging field of I5.0 by developing an assessment model grounded in

STT principles, addressing calls in the literature to apply STT across diverse research domains [119]. By employing the STT framework, this study provides valuable insights into I5.0 dynamics and integrates its findings into the broader body of knowledge, promoting scholarly dialogue and advancing theoretical understanding in several key areas.

Firstly, the study bridges the social-technical divide by recognizing I5.0 as a holistic system, wherein successful implementation relies on the joint optimization of both social and technical systems. This STT-informed assessment model provides a more nuanced understanding of I5.0, integrating social and technical aspects rather than examining them in isolation. As a result, it ensures the development of systems that are not only innovative and efficient but also ethical, inclusive, and capable of promoting environmental and social well-being.

The study also contributes to the theoretical discourse on human-machine collaboration. The STT framework facilitates the evaluation of human factors, such as skill development, work-life balance, and safety, as well as technological advancements. This integrated approach significantly enhances the theoretical understanding of human-machine collaboration in the I5.0 ecosystem, where both elements are critical to success.

Moreover, the assessment model encourages organizations to evaluate how well prepared their social systems are to manage the disruptions and transformations introduced by new technologies. This perspective offers a deeper theoretical understanding of organizational resilience and adaptability in the face of technological change.

Lastly, the study addresses the mitigation of unintended consequences and ethical considerations associated with I5.0 adoption. By explicitly considering the social implications of technological advances, such as job displacement, skill gaps, and data privacy concerns, the model advances theoretical discussions on the ethical dimensions of I5.0. It promotes responsible integration of I5.0 technologies, ensuring that organizations consider both the opportunities and the potential risks posed by these innovations.

8.2. Contribution to practice

The assessment model developed has substantial practical implications for organizations embarking on their I5.0 transformation. First, it simplifies strategic decision-making by providing a clear framework for evaluating an organization's current readiness for I5.0. This framework enables organizations to make informed decisions on resource allocation and prioritize initiatives that facilitate a smoother transition to I5.0 practices.

The model also serves as a dynamic roadmap for continuous improvement. By enabling organizations to systematically assess their progress and measure advances over time, it supports ongoing adaptability and refinement of I5.0 strategies. Furthermore, by embedding ethics in practice, the model guides organizations towards responsible technology deployment, sustainable resource management, and environmentally conscious manufacturing. These activities, in turn, enhance brand reputation and foster positive societal impact, aligning with the values of modern consumers and stakeholders.

Finally, the model helps bridge the gap between industry and policy. The insights derived from the assessment can inform policymakers' crafting of I5.0-supportive initiatives (e.g., governmental policies, regulations, standards, and publicly funded incentives) to align with industry needs and best practices. This alignment not only benefits individual organizations but also strengthens the broader industrial ecosystem by fostering innovation and supporting sustainable growth.

8.3. Limitations

While the assessment model provides a framework for guiding I5.0 transformations, several limitations must be acknowledged. First, generalizability remains a concern. The model may not be universally applicable across all sectors, industries, or organization sizes. The diverse nature of I5.0 implementation necessitates a more tailored approach, considering industry-specific requirements, regional contexts, and organizational cultures to ensure relevance and efficacy.

A second limitation arises from the rapid pace of technological change. As I5.0 technologies continue to evolve, certain assessments and recommendations may become outdated. Given the fast-moving landscape of technological innovation, the model may require frequent updates to stay aligned with new developments.

Lastly, cultural considerations pose a considerable challenge. Organizational practices and priorities can differ significantly across cultures, necessitating the model's adaptation to ensure a culturally sensitive approach. Without such adaptation, the model may not fully capture the unique dynamics of each culture, potentially limiting its practical effectiveness in diverse cultural settings.

8.4. Scope of future research

The field of research on I5.0 is broad and promising in scope, and essential for advancing scientific understanding of its implications and theoretical foundations. Future research can address several key areas to enhance both theoretical and practical knowledge.

Assessment quantification emerges as a critical research avenue. While this study develops a holistic assessment model, it intentionally refrains from assigning quantifiable metrics to each dimension or generating a global score for organizational readiness. Future research could focus on creating quantitative measures to give companies a clearer evaluation framework.

Another significant opportunity lies in evaluating the long-term impact of I5.0 through longitudinal studies. These studies would provide valuable insights into the sustained effects of I5.0 adoption, particularly on human-machine collaboration, workforce skills development, and changes in organizational culture over time.

Similarly, future research should explore methodologies to distinguish these dimensions systematically while preserving their interconnected nature. Potential approaches include leveraging multi-criteria decision-making techniques, causal loop diagrams, or network-based analyses to map relationships between categories more precisely. Developing distinct yet interrelated metrics for each dimension can also help measure their contributions independently, while still acknowledging their shared impact on I5.0 implementation.

Benchmarking of best practices across industries and regions is also an essential direction for development. Comparative studies could identify the most effective approaches to I5.0 implementation, facilitating the sharing of best practices and accelerating successful adoption.

Additionally, regulatory frameworks and compliance studies represent a crucial area of research. Exploring how legal and regulatory systems influence the interplay between social and technological systems could yield insights into best practices for ensuring compliance while fostering innovation.

Finally, real-world case studies of industry-specific I5.0 adoption would yield practical insights into how organizations can effectively navigate the complexities of the I5.0 transition. Such case studies could provide concrete examples and actionable strategies to guide businesses on their transformation journeys.

CRediT authorship contribution statement

Cesar Cuevas-Lopez-de-Baro: Writing – original draft. **Ignacio Mira-Solves:** Supervision. **Antonio Verdú-Jover:** Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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Barriers to Industry 5.0 adoption and perception-based differences between Lean and non-Lean Six Sigma firms

Abstract

Industry 5.0 (I5.0) extends Industry 4.0 by emphasizing sustainability, human-centricity, and resilience as core pillars of future industrial development. However, its practical implementation is constrained by limited understanding of organizational barriers, particularly in Continuous Improvement (CI) contexts. This study examines barriers to I5.0 adoption and compares organizational readiness between firms with and without Lean Six Sigma (LSS) experience.

We applied a mixed-methods approach, combining a two-round Delphi study with 19 experts, literature review, and a comparative case analysis of two companies: one LSS-mature and one without LSS implementation. The findings highlight 15 key barriers, with the most critical being limited strategic vision, cultural resistance to change, and insufficient leadership engagement.

The LSS-mature firm showed higher readiness for I5.0, especially in resilience and strategic alignment. The non-LSS firm was perceived as less prepared across all pillars. Based on these results, we mapped LSS tools to the identified barriers, providing a structured approach to implementation.

This study contributes to the emerging I5.0 discourse by clarifying key implementation barriers and demonstrating how CI methodologies support socio-technical transformation.

Managerial relevance statement

This study identifies and prioritizes barriers to I5.0 adoption, offering actionable guidance for both engineering managers and policymakers. Mapping specific LSS tools to each barrier offers

structured methods to address critical, and often underestimated, challenges such as strategic misalignment, leadership inertia, and cultural resistance.

Engineering managers can apply these insights to design targeted improvement initiatives, enhance cross-functional collaboration, and strengthen organizational readiness for sustainable, human-centric, and resilient operations. Policymakers can develop supportive regulatory frameworks, targeted financial incentives, and workforce development programs aligned with I5.0 principles. The comparison of LSS-mature and non-LSS organizations reveals notable differences in readiness, underscoring the strategic value of CI cultures.

The results bridge theory and practice by providing engineering leaders and policymakers with operational tools to integrate socio-technical and process excellence, ensuring technology transitions that are feasible, resilient, and aligned with societal value creation.

Keywords

Case study; Delphi study; human-centricity; implementation barriers; Industry 5.0; Lean Six Sigma; resilience; sustainability.

I. INTRODUCTION

Industry 5.0 (I5.0) marks a shift from Industry 4.0's (I4.0's) technology-driven focus to a holistic framework that prioritizes sustainability, human-centricity, and resilience. Although I4.0 emphasized technological advances and industrial interconnectivity [1], its focus on financial and technological progress often overlooked social and environmental consequences [2]. I5.0 paradigm, articulated in an influential European Commission policy brief [3], responds to these shortcomings by envisioning a future in which technological innovation harmonizes with societal well-being and environmental stewardship [4].

I4.0 represented a paradigm shift toward digitalization, automation, and interconnectivity, emphasizing cyber-physical systems, the Internet of Things, and artificial intelligence, but has been increasingly criticized for its narrow techno-economic focus. Despite significant productivity gains, I4.0 often overlooked broader societal, environmental, and human implications [5]. Scholars and policymakers increasingly argue that industrial transformation must be not only smart and connected but also socially responsible and inclusive.

In 2021, a European Commission white paper argued that I5.0 added three critical elements missing in the automatic factory: environmentally friendliness, human-orientation, and resilience [6]. I5.0 not only extends I4.0 but also reorients industrial policy and practice at a philosophical level. According to Leng et al. [5], the transition to I5.0 must integrate human intelligence and creativity with advanced technologies to ensure value creation that is both ecologically sustainable and socially equitable. Unlike I4.0's tendency to prioritize automation and efficiency, I5.0 emphasizes complementarity of human skills and machine capabilities, workers' long-term well-being, and robust systems to face uncertainty. This evolution marks a shift from automation-driven manufacturing toward human-aware socio-technical ecosystems, where innovation is measured not only by output but also by its impact on people and the planet [5].

I5.0 rests on three fundamental pillars: Sustainability envisions technology that drives economic growth while safeguarding the planet [7], Human-centricity prioritizes workers' well-being, leveraging advanced technologies for prosperity beyond economic growth [3], and Resilience emphasizes organizations' capacity to operate under adversity, recover swiftly, and thrive in dynamic environments [8].

Among CI methods in organizational management, Lean Six Sigma (LSS) stands out as a model of efficiency and quality [9]. The LSS framework for organizational improvement has demonstrated robustness for decades [10]. Rooted in the Toyota Production System, Lean

Production initially emphasized eliminating waste in manufacturing environments [11]. Womack et al. [12] generalized this philosophy as Lean Thinking, applicable across industries. Six Sigma, developed at Motorola and popularized by General Electric, complements Lean by focusing on variation reduction through statistical process control (SPC) [13]. Combining Lean's waste elimination with Six Sigma's defect reduction produced LSS's structured, data-driven approach to CI [14].

Lean principles inspired field-specific adaptations (e.g., Lean Logistics, Lean Construction, Lean Office, Lean Product Development, Lean Project Management, Lean-Green) that typically tailor Lean tools to specific operational contexts without fully integrating LSS's statistical rigor and cross-functional frameworks. LSS's more comprehensive standardized methodology supports performance excellence across processes and industries. We analyze the LSS framework for its maturity, versatility, and compatibility with I5.0's multidimensional goals, a concept that Kaswan et al. describe as Lean 5.0 [15]. I5.0 thus effectively supports engineering management's pursuit of operational efficiency while ensuring that technical outcomes align with organizational goals and broader societal objectives.

Despite I5.0's growing conceptual relevance and its perceived role in driving the next industrial transformation [16], its implementation remains fragmented and lacks practical grounding. Garrido et al. [17] emphasize the need for empirical studies to guide adoption. Most studies focus on enabling technologies or policy frameworks, while far fewer examine organizational-level barriers to adoption. In particular, little is known about how firms' internal capabilities shape perceptions of these barriers. This gap is critical because companies with structured approaches such as LSS may be better prepared to address I5.0's complex challenges.

Recent literature highlights this disconnect and calls for pragmatic, implementation-oriented research to help organizations translate I5.0 values into practice. Borchardt et al. [18] stress lack of practical frameworks and scholarship on I5.0's implications for business management.

Osuna-Velarde et al. [19] argue the need for continuous exploration and pragmatic solutions. Sharma et al. [20] stress mixed-methods approaches for a more comprehensive perspective, and Mukherjee et al. [21] call for research and development to implement this paradigm shift effectively. As Marcon et al. [22] point out, digital technologies are reshaping factory activities, and it is essential to support workers and their social environment, as these are now in the spotlight of manufacturing improvements.

Our study addresses these needs by identifying and analyzing major barriers to I5.0 adoption and exploring how experts at companies with contrasting LSS maturity levels (LSS-mature, no exposure to CI methods) perceive these barriers. We synthesize insights from a Delphi study, a systematic literature review, and exploratory case studies to build a framework to understand and navigate obstacles to I5.0 implementation. This comparison provides valuable insights into the role structured methodologies like LSS play in smoother transitions. Linking these barriers to specific LSS tools provides actionable guidance for engineering managers to align operational excellence with I5.0 principles.

Our study addresses two main research questions: (1) What are the key barriers to I5.0 implementation? (2) What perception-based differences exist between LSS and non-LSS firms? To answer these questions, we pursue four specific objectives: (1) identify and classify key barriers hindering I5.0 adoption, using expert consensus and existing literature, (2) prioritize these barriers through a structured Delphi method, assessing their perceived importance and impact across organizational contexts, (3) compare organizational perceptions of barriers via exploratory case studies of contrasting companies (with/without extensive LSS experience) to understand how CI maturity influences I5.0 readiness, and (4) map specific LSS tools to each barrier to propose a structured approach for engineering managers adopting I5.0.

The findings emphasize the importance of aligning industrial needs with broader societal and environmental objectives, provide actionable guidance for practitioners, and advance theoretical understanding. The remainder of the paper is structured as follows: Section 2 outlines the methodology, Section 3 presents the results, and Section 4 discusses their practical and theoretical implications.

II. MATERIAL AND METHODS

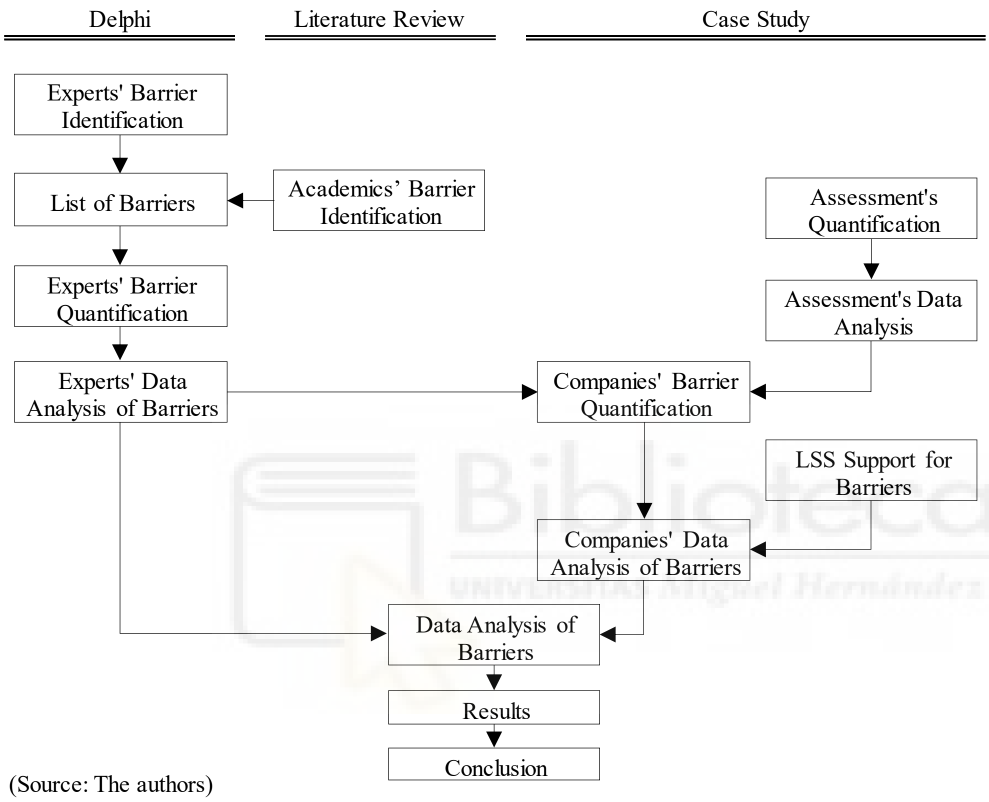
This study employs a mixed-methods design suited to exploratory research. The approach integrates expert consensus with literature review and contextualized organizational perspectives on barriers to I5.0 implementation. In line with Ivert et al. [23], this triangulation enhances the reliability of the findings and deepens understanding of the complex challenges associated with I5.0 adoption. Specifically, the triangulation (1) gathers expert consensus on key barriers to I5.0 adoption, (2) ensures theoretical robustness by synthesizing academic literature, and (3) validates and contextualizes findings within organizational settings, thereby ensuring methodological rigor, theoretical depth, and practical insight.

We evaluated I5.0 by measuring its perceived importance for organizational resource allocation and by assessing each company's perceived ability to overcome barriers (see Section III, Results). Both assessments employed a widely recognized five-point Likert scale: (1) Not Important: minimal or no relevance to organizational goals; (2) Slightly Important: some relevance but not a key focus area; (3) Moderately Important: contributes to strategy though not critical; (4) Important: significantly impacts success and warrants attention; and (5) Extremely Important: essential to achieving strategic goals and long-term adaptability.

We distinguish between general challenges (such as evolving demands, structural shifts, and conceptual tensions) and barriers (defined as factors that actively hinder, delay, or obstruct the implementation of I5.0 principles in organizational settings). Our analysis focuses specifically on barriers as tangible obstacles that organizations must overcome to successfully adopt I5.0

paradigm. We then examine the results and explore potential reasons for differing perceptions, both within each company and across cases, while emphasizing the role of LSS tools in addressing the identified barriers. Figure 1 illustrates the research protocol.

Figure 1: Research protocol



(Source: The authors)

A. Delphi study

We chose the Delphi method because it can generate consensus among experts in fields lacking established frameworks and applied von der Gracht's [24] technique, used widely and successfully to aggregate expert opinions on future developments. The panel of 19 experts with diverse expertise and experience in I5.0 ensured representation across company sizes, industries, sectors, geographic locations, and stages of I5.0 implementation (Table I).

The expert selection criteria were designed to ensure both diversity and relevance. Experts met at least two of the following criteria: (i) professional experience of 5+ years in industrial transformation, quality management, or sustainability; (ii) active involvement in I5.0-related projects or research; (iii) affiliation with organization implementing or exploring I5.0 principles; (iv) publication record or participation in digital transformation policy initiatives, LSS, or socio-technical innovation. To maximize generalizability, we drew experts from varied sectors (manufacturing, services, public entities, academia, research institutes) and 14 geographical contexts.

Table I: Description of participating companies and expert characteristics

Company size		Type		Sector		Country		I5.0 stage implem.	
<10 empl.	5	Private	14	Manufac. & Const.	7	Belgium	1	Not started	3
11-50 empl.	4	Public	5	Services	6	Czech Republic	1	Initial stages	7
51-249 empl.	4			Public entities	2	Germany	2	Partially impl.	6
>250 empl.	6			Academia	2	Hungary	1	Widely impl.	3
				Research institute	2	Ireland	1		
						Italy	3		
						Netherlands	1		
						Portugal	1		
						Romania	2		
						Serbia	1		
						Slovenia	2		
						Sweden	1		
						Switzerland	1		
						United Kingdom	1		

(Source: The authors)

The Delphi process had two rounds. In Round 1 - Barrier Identification, experts identified barriers organizations encounter in I5.0 implementation, including four areas with broad thematic categories that grouped related dimensions to structure understanding of challenges to I5.0 adoption. These areas were I5.0 pillars (sustainability, human-centricity, resilience) and a fourth overarching area of challenges spanning all three pillars (e.g., resource allocation, regulatory frameworks, strategic alignment). We further divided each area into specific dimensions—distinct challenges, concepts, or factors shaping I5.0 adoption. This initial barrier identification was refined through a literature review. In Round 2 – Barrier Quantification, experts scored and provided qualitative insights on the final list of barriers, refining areas shared in Round 1 by incorporating feedback from the broader expert panel. This dual approach prioritized barriers and enriched contextual understanding through expert discourse. Iterative design thus refined the initial areas while maintaining the Delphi method's structured consensus-building benefits.

B. Literature review

The systematic literature review consolidated and synthesized academic knowledge on I5.0 and its integration with LSS, complemented Round 1 findings of the Delphi study, and was utilized in Round 2. For Wankhede and Vinodh [25], this approach ensures evidence-based identification of barriers. Table II presents the selection criteria for the literature review, which followed Tranfield et al.'s [26] method, using Web of Science (WoS) and Scopus. These main bibliographic databases for field delineation lead scholarly impact and indexing of high-quality journals [27]. Our search showed that 76% of WoS articles were also in Scopus. Articles marginally related to the subject through data curation were excluded.

Table II: Literature Review Criteria

Research databases	WoS, Scopus
Publication type	Peer-reviewed OR Early access article
Language	Only English
Search period	2020-2024
Search field	Title, keywords, or abstract
Search terms	("industry 5.0" OR "ind5.0" OR "ind.5.0" OR "I5.0") AND (barrie*)
Inclusion criteria	Articles exclusively on I5.0 and barriers
Exclusion criteria	Articles using I5.0 as supportive concept only

(Source: The authors)

C. Case study

Explanatory case study of two companies helped contextualize the barriers identified and explore variations in organizations' I5.0 readiness. It also validated and further explored barriers identified through the Delphi methodology and literature review. Explanatory case study is appropriate given our goal to understand, describe, and illustrate challenges companies face in adopting I5.0 and considering researchers' external position. This approach aligns with Martinsuo and Huemann [28], who advocate case studies to explore complex practical phenomena in depth. Yin [29] defines case study as empirical investigation of a contemporary phenomenon in context, especially when phenomenon-context boundaries are not clear. Highly suitable to examine multifaceted barriers to I5.0 implementation, our approach enabled holistic understanding of the challenges in their organizational settings.

Company 1, a subsidiary of a globally recognized pharmaceutical brand renowned for high product quality and manufacturing efficiency, employed 520 people, generated an annual revenue of €550 million, and had operated for 21 years. The company has a 15-year history of LSS implementation and a clear strategic vision, anticipating future challenges requiring innovation and stricter compliance with government regulations. Company 2, a textile retailer, takes a global market approach focusing primarily on internal design and distribution while outsourcing supply chain operations. It employed 93 people, reported annual revenue of €83 million, and has experienced rapid growth throughout its 15-year history.

These companies are suitable for case study based on their contrasting industry contexts, operational structures, and LSS maturity levels. We chose the pharmaceutical company due to its strong regulatory environment, high manufacturing complexity, and extensive LSS experience. Its well-established process optimization culture and structured approach to CI are ideal for assessing how operational excellence practices influence I5.0 adoption. The textile retailer represents a more dynamic, design-driven industry, with rapid growth and supply chain outsourcing, enabling examination of I5.0 barriers in a less process-driven, highly competitive sector where agility and adaptability are crucial. Neither company had prior knowledge of the I5.0 paradigm, although both demonstrated strong understanding of the I5.0 pillars.

Observation units were three managers from each company: Human Resources (HR), Sustainability, and LSS (Company 1) and HR, Logistics, and Sustainability (Company 2). Managers were the primary data sources, and we remained objective throughout data collection and analysis.

These specific managerial roles were selected due to their direct involvement with the three I5.0 pillars. HR is crucial to I5.0 implementation in overseeing workforce adaptation, skills development, and change management. I5.0's strong emphasis on human-centricity makes HR valuable for insights into challenges of employee engagement, training, and job transformation. Sustainability Managers' insights into regulatory compliance, green manufacturing practices, and circular economy initiatives help identify barriers involving sustainable operations, resource efficiency, and long-term corporate responsibility. We chose the pharmaceutical company's LSS Manager due to the company's extensive history of LSS implementation, as this role provides expertise in process optimization, quality management, and efficiency improvements, factors critical to understanding engineering operational challenges of I5.0 adoption. As supply chain agility and distribution efficiency are central in textile retail, we chose Company 2's Logistics Manager to capture barriers to outsourcing, global supply chain coordination, and integration of I5.0 principles in a fast-paced retail environment.

Examining these managerial roles across companies ensures balanced multidisciplinarity, capturing human, environmental, and operational barriers; enhancing validity of the findings; and enabling comparison of different viewpoints within the same company.

We conducted face-to-face interviews in three phases. First, participants quantitatively evaluated company readiness for I5.0 implementation based on a specific I5.0 assessment [30]. Second, they quantified each barrier's importance in the organizational context. Third, Company 1's LSS Manager explored potential tools to overcome each barrier identified. Semi-structured interviews conducted on site, December 2024–January 2025, lasted 90-210 minutes.

Before the interviews, participants received both documents and had one week to familiarize themselves with the material.

For each barrier, we calculated average (AVE) and range (RAN) using IBM SPSS to quantify perceived importance and variability across participants. AVEs gave a central measure of critical participants' beliefs about each barrier. RANs gave degree of divergence in experts' opinions, highlighting areas of consensus/disagreement.

The conducted semi-structured interviews enriched the quantitative findings, adapting questions slightly to incorporate diverse viewpoints, following Yin's [29] recommendations for case study. This approach nuances understanding of how organizations perceive and experience the challenges in practice and has demonstrated validity in similar technology adoption studies (e.g., Amin et al. [31]). Finally, we documented and later collaboratively analyzed open-ended comments.

III. RESULTS

This section presents the barriers to I5.0 adoption identified, prioritizes them, compares organizational perceptions across firms, and maps specific LSS tools to address these barriers.

A. Delphi study - Round 1

Round 1 of the Delphi study addressed the first research question. Experts identified and elaborated on potential barriers to I5.0 implementation. Based on their diverse professional backgrounds and experiences, the experts generated a comprehensive list of barriers encompassing practical organizational constraints and broader systemic and cultural issues.

For Sustainability, experts noted challenges such as integrating circular economy principles, implementing energy-efficient technologies, and measuring carbon footprints, highlighting tensions between environmental goals and operational efficiency.

Human-centric barriers affected workforce adaptation—resistance to change, need to upskill and reskill employees, difficulty fostering a culture of innovation and creativity. Experts also noted challenges in designing technologies that collaborate effectively with human workers, stressing the importance of balancing technological advance with human well-being.

For Resilience, experts noted barriers to developing adaptable and flexible processes, establishing effective risk management systems, and quantifying organizational resilience, reflecting organizations' growing need to build robust systems that withstand disruptions and adapt to dynamic environments.

Experts stressed Overarching barriers such as I5.0's misalignment with existing business models, lack of clear regulatory frameworks, financial constraints, and no clear roadmap to transition to I5.0. Challenges underscored the need for strategic clarity and external support to facilitate adoption, illustrating how engineering managers design synergies between technological capabilities with overarching business objectives.

B. Literature review

The literature review's complementary insights expanded on barriers identified in Round 1 of the Delphi study, analyzing 77 articles from WoS and 73 from Scopus to reveal different dimensions involving I5.0 adoption barriers (Table III).

Table III: Areas and dimensions from literature review

Dimension	Concept	Ref.
Sustainability		
Sustainable policies	Broader focus on sustainability is key to I5.0's focus on societal value and wellbeing. Includes emergence of sustainable policies, minimal waste generation, commitment to conserve resources and address climate targets.	[32] [33]
Energy savings	Adopting I5.0 practices increases energy savings for sustainability and cost-efficiency, particularly in resource- and energy-intensive industries.	[34]
Technological obsolescence	Despite technological evolution of electronic products, short lifespan and frequent replacement have caused a surge in discarded equipment. Responsible e-waste management is crucial to maintain sustainability goals.	[7]
Circular economy	Circular economy principles are indispensable for sustainable I5.0 implementation, especially in firms aspiring to compete internationally. Involves designing products for longevity, reusability, recycling.	[35]
Life cycle assessment	Thorough life cycle assessments of I5.0 technologies and processes help identify and address environmental impacts at each stage, facilitating informed sustainable decision-making.	[36]

Carbon footprint	New technologies have significant carbon footprint due to use of scarce raw materials and energy consumption in manufacturing, operations, recycling. Efficiency can be assessed through various metrics (carbon emissions, power consumption) to reduce greenhouse gas emissions	[37]
Human-Centrism		
Human-centric approach	I5.0's human-centric approach empowers workers by prioritizing their well-being and individual skills, a significant challenge for traditional manufacturing practices.	[38]
Human-machine collaboration	I5.0 stresses human-machine collaboration so humans can intervene when needed and incorporate critical thinking and adaptability. Supports, not supersedes, human workers, fostering more balanced, efficient work environment.	[32]
Upskill and reskill training	Upcoming production systems require specialized skills, producing surge in higher-competency positions and significantly reducing roles requiring lower credentials. Successful adaptation to this transformation pushes companies toward new work and organizational models, necessitating strategies to upskill and reskill workers.	[20], [39], [40]
Creativity	Challenges in I5.0 adoption include perception, willingness, ability, financial scope of businesses, need for a human-centric approach. Overcoming these challenges involves focusing on creative research and knowledge.	[32]
Talent attraction and retention	I5.0 enhances creativity, innovation, and critical thinking skills, increasing businesses' attractiveness to potential employees	[41]
High-quality jobs	Successful I5.0 policy generates high-quality jobs and fosters workers' economic growth	[16]
Improved design freedom for workers	By automating manufacturing processes through I5.0, workers increase focus on delivering improved, bespoke services/products, enabling greater design freedom and job satisfaction.	[42]
Worker empowerment	I5.0 empowers workers and addresses employees' evolving skills and training needs. Empowers workers through knowledge development and participation in innovative processes.	[43]
Resistance to change	Organizations' resistance to change can hinder successful adoption of I5.0 significantly. Overcoming resistance and fostering a culture of innovation and CI is crucial.	[32]
Resilience		
Human flexibility	I5.0 promotes resilience by enabling customized, software-connected factories and advanced technology adoption. May require additional time and effort from human workers but improves businesses' ability to adapt effectively to changing circumstances and challenges.	[44]
Increased general resilience	I5.0 adoption promotes economic performance and resilience, so businesses adapt to a changing world and emerging markets more effectively.	[44]
Ability to adapt	Organizations may face challenges in adapting to I5.0 concept, such as integrating knowledge circulation, fostering dialogue among subsystems, adapting technology and entrepreneurial strategies to operating environment.	[45]
Adaptable, flexible manufacturing processes	I5.0 shifts from traditional mass production to more flexible, adaptable manufacturing processes. Involves optimizing manufacturing processes for personalization and sustainability, collaborating with suppliers and partners, and developing a culture of innovation and CI.	[46]
Risk management	I5.0 era presents serious security threats to organizations. Implementing comprehensive risk management strategies mitigate unforeseen challenges and ensures continuous operations	[47]
Overarching		
New business models	I5.0 adoption requires recognition of and openness to novel work methods. May entail transition to new business models, reconfiguring organizational architecture, competitive advantage, value creation and monetization.	[48]
Leadership and management	Shift to I5.0 accentuates humans' role in digital systems, environmental awareness, sustainability. Requires alternative approach to leadership and management, with greater emphasis on trust, empowerment, and collaboration.	[49]
Impact on stakeholders	In-depth understanding of how smart systems influence different stakeholders (e.g., employees, customers, environment) needed to integrate these technologies successfully in manufacturing.	[50]
Competitiveness	I5.0 fosters strategies to enhance businesses' appeal to potential investors, employees, consumers, especially in specialized market segments.	[51]
Enhanced efficiency and productivity	Embracing I5.0 paradigm involves intelligent collaboration of human operators and well-designed machines that may heighten efficiency and productivity.	[52]
Personalized products and services	I5.0 focuses on meeting personalized demands, yielding enhanced customer satisfaction through personalized products/services.	[50]
Financial investment	Financial burden of I5.0 adoption hinders numerous organizations, reducing ability to embrace this paradigm and becoming a barrier for some.	[53]
Regulatory frameworks	Clear regulatory frameworks must guide ethical, responsible I5.0 deployment. Proactive regulatory measures must govern I5.0's disruptive force and controversial sustainability implications; employees must adapt to continually evolving technology and address potential societal implications.	[54]

Lack of research and development	Limited (nascent) research on I5.0 context hinders widespread adoption. Significantly more R&D efforts are needed to ground well-informed, successful implementation of this transformative paradigm	[21]

(Source: The authors)

While this literature review stresses key barriers to I5.0 adoption, Section IV Discussion examines its contribution to the Delphi study.

C. Barriers

Combining the experts' insights and literature review findings, we developed a detailed list of barriers companies face when implementing I5.0. This approach provides a framework for understanding barriers, facilitates evaluation of companies' readiness for I5.0 adoption, and identifies priority areas. Integrating expert insights and literature review findings enhances the list's robustness for academic research and practice. Table IV presents the barriers corresponding to the first specific objective.

Table IV: Detailed list of barriers organizations face when implementing I5.0

Dimension	**Barrier**	**N**
Sustainability		
Sustainable policies	I5.0 principles not aligned with sustainability policies	1
Energy saving	Energy-efficient technologies and practices to reduce carbon footprint	2
Circular economy	Implementation of circular economy principles	3
Life cycle assessment	Conducting life cycle assessments of products and processes to identify environmental impacts	4
Carbon footprint	Measuring and reducing carbon footprint	5
Human-centricity		
Human-centric approach	Enhancing organization's human capabilities and well-being	6
Human-machine collaboration	Human-machine integration to optimize productivity and efficiency	7
Training	Training and development for employees to acquire I5.0 skills	8
Creativity	Fostering employee culture of innovation and creativity	9
Attracting and retaining talent	Attracting and retaining skilled talent for I5.0 implementation	10
Worker empowerment	Empowering employees to take ownership of their work and contribute to decision-making	11
Resistance to change	Resistance to change within organization	12
New technology design	New technologies not designed to collaborate effectively with humans	13
Resilience		
Increased overall resilience	Developing a resilience strategy to handle disruptions and uncertainties	14
Adaptable and flexible processes	Processes and systems not flexible enough to adapt to changing conditions	15
Constant change	Organization not prepared to manage constant change and innovation	16
Risk management	No effective risk management processes to identify and mitigate risks	17
Resilience quantification	Unclear methods to quantify organization's overall resilience	18
Overarching		
Business model	I5.0 principles (sustainability, human-centrism, resilience) not aligned with business model	19

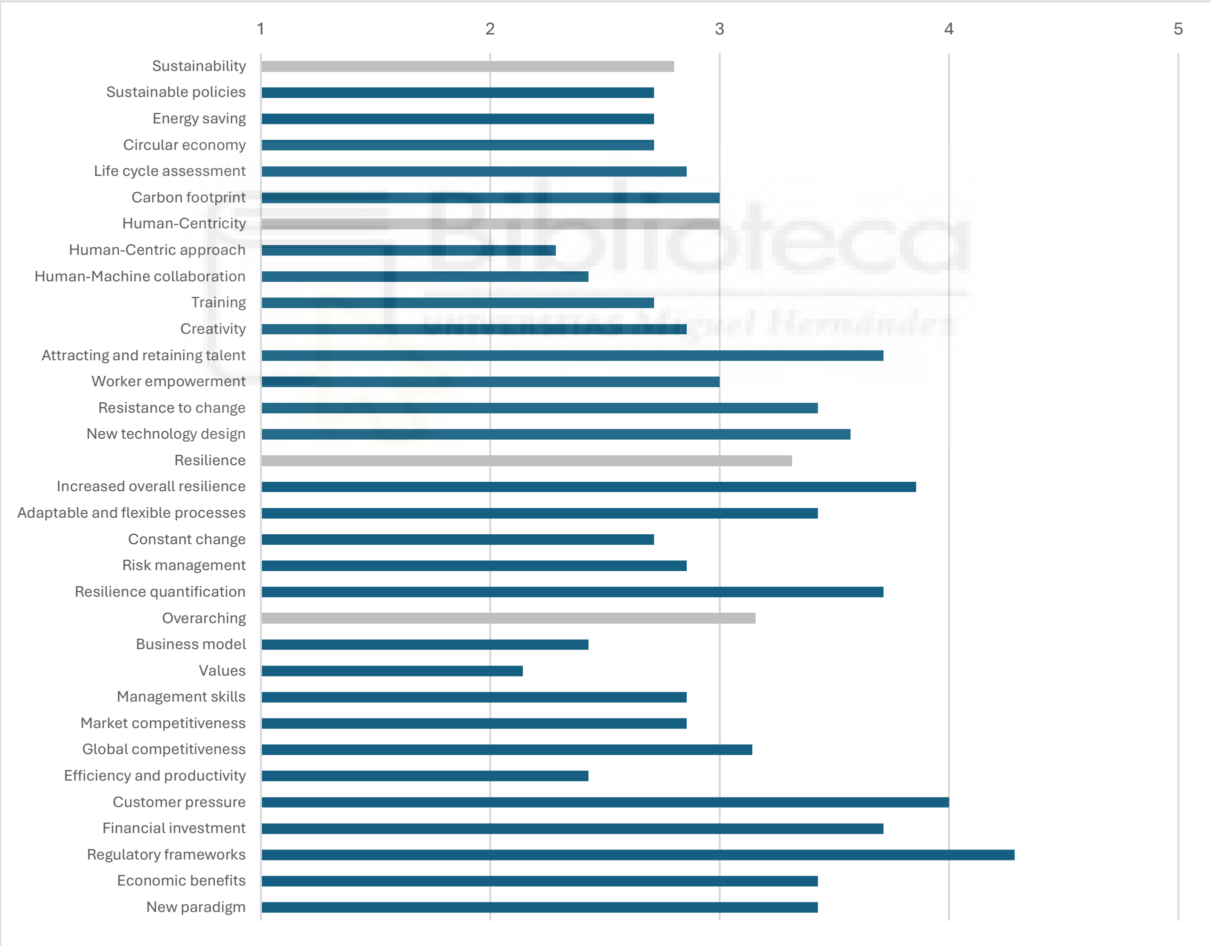
Values	I5.0 principles not aligned with organizational values	20
Management skills	Leadership team lacks skills and experience to guide I5.0 implementation.	21
Market competitiveness	Unclear how I5.0 will provide competitive advantage in market	22
Global competitiveness	Non-compliance with I5.0 regulations in other countries reduces competitiveness.	23
Efficiency and productivity	I5.0's potential to improve organization's efficiency and productivity unclear.	24
Customer pressure	Customers do not demand implementation of I5.0 principles.	25
Financial investment	Insufficient financial resources for I5.0 implementation	26
Regulatory frameworks	No clear regulations and standards for I5.0	27
Economic benefits	Unclear economic benefits to implementing I5.0	28
New paradigm	I5.0 principles, methods, tools unclear; no roadmap for transition	29

(Source: The authors)

D. Delphi study - Round 2

Expert ratings of each barrier's importance achieved our second specific objective (Figure 2).

Figure 2: Experts' average ratings of perceived importance for each Industry 5.0 barrier



(Source: The authors)

Sustainability: Within Sustainability, barriers of carbon footprint, life cycle assessment, and energy saving were moderately important. Experts rated alignment of I5.0 principles with sustainable policies and circular economy adoption similarly. Sustainability was less critical than other areas, perhaps reflecting varying levels of organizational readiness and priority to environmental concerns due to government regulations.

Human-Centricity: Human-centric challenges were talent attraction and retention, resistance to change, and worker empowerment, as well as integrating new technologies to collaborate effectively with humans, because technology must align with human-centric principles.

Enhancing human capabilities, providing training, and fostering creativity were rated as less critical, suggesting that organizations recognize the value of human-centric approaches but focus more on challenges to external technological and talent acquisition than on internal cultural and training efforts.

Resilience: Resilience-related barriers scored high, developing resilience strategies and quantifying organizational resilience being the most critical. Organizations must increasingly build adaptive, flexible processes and enhance risk management capabilities. As to constant change, organizations acknowledge change but may not yet view it as an immediate obstacle compared to broader resilience metrics.

Overarching: These barriers varied in importance, with regulatory frameworks and customer pressure as the most critical. Lack of clear standards and customer demand highlight fundamental misalignment between organizational strategies and external ecosystem required for successful I5.0 implementation. Need for financial investment and unclear economic benefits also rated high, indicating financial uncertainty as a key constraint.

Barriers involving organizational values, business models, and efficiency and productivity were perceived as less important. Although foundational alignment with I5.0 principles remains essential, organizations may not yet view these elements as immediate priorities compared to external pressures such as regulatory demands.

E. Case study

We achieved the third specific objective through case study, due to limited knowledge on I5.0 in general and barriers in particular. Following Yin [29], these case studies provide empirical insights into key principles, not a representative sample. The first phase assessed company perspective on I5.0 adoption to establish baseline understanding of company priorities in implementing I5.0. The second analyzed specific barriers, both between companies and among individual interviewees, and whether applying LSS tools influenced perceived significance of certain barriers, potentially reducing their impact. This phase yielded critical insights into the most pressing obstacles and potential mitigation strategies.

Case study - I5.0 assessment

The results indicate that Company 1 stresses Sustainability slightly more than Human-Centricity, although all four areas showed similar importance. Figure 3 presents simplified assessment results, highlighting the 25% highest and lowest scores.

Figure 3: I5.0 readiness evaluation scores by functional role

	Company 1					Company 2				
	HR	LSS	Sust.	All 3		HR	Log	Sust	All 3	
Areas and Dimensions	AVE	AVE	AVE	RAN	AVE	AVE	AVE	AVE	RAN	AVE
All areas	1.7	1.7	4.1	2.4	2.5	2.2	2.4	2.3	0.2	2.3
Sustainability	2.2	2.2	4.3	1.3	2.9	1.8	2.1	2.6	1.6	2.1
Resource efficiency	3.0	3.0	5.0		3.7	2.3	1.7	2.0		2.0
Circular economy	2.7	2.7	4.0		3.1	1.3	2.0	2.0		1.8
Integration of renewable energies	1.7	1.7	4.0		2.4	1.0	1.0	2.7		1.6
Eco-friendly materials	1.7	1.7	4.0		2.4	1.7	2.3	2.3		2.1
Supply chain	1.5	1.5	4.0		2.3	1.5	2.0	3.5		2.3
Social sustainability	2.7	2.7	4.7		3.3	2.7	3.7	3.0		3.1
Human-Centricity	1.4	1.4	4.1	0.8	2.3	2.1	2.3	1.9	0.9	2.0
Collaboration people and machines	2.0	2.0	4.3		2.8	1.7	1.7	1.3		1.6
Skills development and training	1.7	1.7	4.0		2.4	2.3	2.5	1.7		2.0
Human safety and ergonomics	1.7	1.7	4.0		2.4	1.7	2.7	2.3		2.2
Work-life balance	1.0	1.0	4.0		2.0	3.0	2.3	2.0		2.4
Personalization of work experience	1.0	1.0	4.0		2.0	2.5	2.0	1.5		2.0
Ethical considerations	1.0	1.0	4.0		2.0	1.3	2.3	2.3		2.0
Resilient	1.6	1.6	4.1	1.2	2.4	2.2	2.2	2.4	2.3	2.3
Cybersecurity and operational safety	2.5	2.5	4.5		3.2	3.5	3.5	4.0		3.7
Adaptive technologies	1.5	1.5	4.0		2.3	2.0	2.0	1.5		1.8
Redundancy and flexibility	1.5	1.5	4.0		2.3	2.0	2.5	2.5		2.3

Data-driven decision making	1.5	1.5	4.0		2.3	1.5	1.5	2.0		1.7
Supply chain resilience	1.5	1.5	4.0		2.3	2.5	2.0	2.0		2.2
Remote operations and collaboration	1.5	1.5	4.0		2.3	3.0	2.5	3.0		2.8
Scenario planning and simulation	1.0	1.0	4.0		2.0	1.0	1.5	1.5		1.3
Overarching	1.9	1.9	4.2	1.2	2.6	2.5	2.9	2.4	0.4	2.6
Vision and strategy	2.7	2.7	4.7		3.3	2.3	3.0	3.0		2.8
Resource allocation	1.5	1.5	4.5		2.5	2.5	3.5	2.5		2.8
Innovation framework	1.5	1.5	3.5		2.2	2.0	3.0	2.5		2.5
Communication strategy	1.5	1.5	3.5		2.2	3.0	3.0	1.5		2.5
Technological preparation	2.0	2.0	4.3		2.8	2.7	2.7	2.7		2.7
Data strategy	2.0	2.0	4.7		2.9	2.7	2.3	2.3		2.4

(Source: The authors)

All Sustainability dimensions scored relatively high, with resource efficiency, the social dimension (stakeholders' needs, equity and diversity, work climate), and circular economy highest. Supply chain, eco-friendly materials, and renewable energies were least important.

For Human-Centricity, human-machine collaboration, skill development and training, and human safety and ergonomics scored highest. On the other hand, work-life balance, personalization of work experience, and ethical I5.0 considerations lowest. Within Resilience, cybersecurity and operational safety were very important, and scenario planning and simulation least important. Finally, Overarching concerns prioritized vision and strategy over communication strategy.

Individual interviewees varied substantially. Scores ranged from 1.7 (HR, LSS) to 4.1 (Sustainability) (RAN 2.4), indicating divergent stakeholder priorities due to differing views on importance of I5.0 areas and dimensions within the organization.

Company 2 rated Overarching and Resilience slightly higher than Sustainability and Human-Centricity, showing consistent perception of their importance across the organization. For Sustainability, the social dimension (stakeholders' needs, equity and diversity, work climate) scored highest, reflecting commitment to social responsibility. Integrating renewable energies scored lowest, suggesting a gap in the company’s sustainability efforts. Within Human-Centricity, work-life balance scored highest and person-machine collaboration lowest. Thus, while the company values employee well-being, embracing human-machine collaboration is not key to its strategy. In Resilience, cybersecurity and operational safety, and remote operations and collaboration scored highest, highlighting strong focus on operational safety and adaptability. Adaptive technologies and supply chain resilience scored lowest, indicating limited preparedness for disruptions and reliance on traditional decision-making processes. For Overarching, vision and strategy and resource allocation scored slightly higher than other dimensions. Data strategy ranked lowest, but all six dimensions showed similar importance.

Managerial perspective varied little among interviewees (2.1–2.4, RAN 0.3). Low variability suggests managers' convergent priorities, reflecting shared understanding of companies' I5.0 goals and challenges.

The companies' results differed most in Sustainability, with no variation in Overarching and minor differences in the four areas. At dimensional level, the companies differed most on resource efficiency and circular economy. Both perceived four dimensions (supply chain, personalization of work experience, ethical I5.0 considerations, redundancy and flexibility) as equally important.

In sum, Company 1's approach to I5.0 appears shaped by its LSS heritage, emphasizing resource efficiency and strategic vision but revealing gaps in communication strategy. Company 2 prioritizes cybersecurity and social sustainability but lags in scenario planning and simulation. These differences likely arise from the companies' distinct organizational cultures, methodologies, and industry contexts, underscoring the significance of prior methodological experience and corporate values shaping I5.0 adoption strategies.

Case study - I5.0 Barriers

Company 1 sees Resilience as most pressing, followed by moderate concerns about Human-Centric and Overarching barriers. While relevant, Sustainability was least significant. Narrow overall response range suggests the three managers perceive these areas as similarly challenging. Figure 4 summarizes the findings.

Figure 4: Perceived barriers to I5.0 implementation across companies and managerial roles

	Company 1					Company 2				
	HR AVE	Sustain. AVE	LSS AVE	All 3 AVE	RAN	HR AVE	Sustain. AVE	LSS AVE	All 3 AVE	RAN
Sustainability	3.0	3.2	2.6	2.9	0.6	3.4	2.8	3.4	3.2	0.6
Sustainable policies	2	1	2	1.7	1.0	3	1	1	1.7	2.0
Energy saving	3	4	2	3.0	2.0	4	4	4	4.0	0.0
Circular economy	4	5	3	4.0	2.0	4	3	4	3.7	1.0
Life cycle assessment	3	2	4	3.0	2.0	5	5	5	5.0	0.0
Carbon footprint	3	4	2	3.0	2.0	1	1	3	1.7	2.0
Human-centricity	3.8	3.3	3.0	3.3	0.8	3.1	3.1	3.6	3.3	0.5
Human-centric approach	3	4	2	3.0	2.0	3	3	3	3.0	0.0
Human-machine collaboration	4	2	3	3.0	2.0	4	4	4	4.0	0.0
Training	5	3	4	4.0	2.0	2	3	5	3.3	3.0
Creativity	3	3	2	2.7	1.0	4	3	3	3.3	1.0
Attracting and retaining talent	5	3	4	4.0	2.0	3	5	5	4.3	2.0
Worker empowerment	3	4	2	3.0	2.0	2	1	3	2.0	2.0
Resistance to change	4	5	3	4.0	2.0	3	4	4	3.7	1.0
New technology design	3	2	4	3.0	2.0	4	2	2	2.7	2.0
Resilience	4.0	3.8	2.8	3.5	1.2	3.6	3.8	3.2	3.5	0.6
Increased overall resilience	4	5	3	4.0	2.0	4	2	3	3.0	2.0
Adaptable and flexible processes	4	4	2	3.3	2.0	2	4	2	2.7	2.0
Constant change	4	3	3	3.3	1.0	2	4	2	2.7	2.0
Risk management	3	4	2	3.0	2.0	5	4	4	4.3	1.0
Resilience quantification	5	3	4	4.0	2.0	5	5	5	5.0	0.0
Overarching	3.3	3.3	3.0	3.2	0.3	3.5	3.1	3.3	3.3	0.5
Business model	2	4	3	3.0	2.0	2	3	2	2.3	1.0
Values	1	1	2	1.3	1.0	1	1	1	1.0	0.0
Management skills	4	3	3	3.3	1.0	3	4	3	3.3	1.0
Market competitiveness	3	2	4	3.0	2.0	4	4	4	4.0	0.0
Global competitiveness	3	5	4	4.0	2.0	5	5	5	5.0	0.0
Efficiency and productivity	2	3	1	2.0	2.0	4	2	3	3.0	2.0
Customer pressure	3	4	2	3.0	2.0	3	1	4	2.7	3.0
Financial investment	5	3	4	4.0	2.0	4	1	1	2.0	3.0
Regulatory frameworks	4	5	3	4.0	2.0	5	5	5	5.0	0.0
Economic benefits	4	2	3	3.0	2.0	4	4	4	4.0	0.0
New paradigm	5	4	4	4.3	1.0	4	4	4	4.0	0.0
All	3.5	3.4	2.9	3.2	0.7	3.4	3.2	3.4	3.3	0.2

(Source: The authors)

For Sustainability, implementing circular economy principles was the most significant hurdle. Energy efficiency, life cycle assessment, and carbon footprint presented moderate challenges but not severe bottlenecks. Sustainability policies scored lowest, suggesting that existing frameworks align well with I5.0 principles. The greatest Human-Centric challenges were training and development for I5.0 skills, attracting and retaining skilled talent, and resistance to change. Fostering employee culture of innovation and creativity was least concerning, suggesting that the company already supports CI. Resilience was the most critical challenge for Company 1. Major concerns were developing strategies to handle disruptions, methods to quantify organizational resilience, and effective risk management. Risk identification and mitigation were less critical than building overall resilience. Among Overarching issues, adopting new I5.0 principles was a major roadblock, highlighting need for a roadmap for structured transition. Additional concerns included global competitiveness, financial investment constraints, and lack of clear regulatory frameworks. Aligning I5.0 principles with organizational values presented only a minor challenge.

Despite their different roles, managers showed no drastic differences in perceptions of I5.0 barriers. The HR Manager's highest AVEs were challenges, which the LSS Manager rated slightly lower. Interestingly, while scores varied widely for some barriers (indicating differing managerial areas), six barriers varied little, suggesting general agreement on their impact.

For Company 2, the most critical barriers to I5.0 adoption involved life cycle assessment, resilience quantification, global competitiveness, and regulatory frameworks. Aligning I5.0 principles with organizational values, sustainability policies, and carbon footprint reduction seemed least problematic.

Among the four challenges, life cycle assessment was the most significant Sustainability-related challenge, with energy-efficient technologies and circular economy principles. The company reported fewer concerns with carbon footprint reduction and policy alignment, indicating progress in environmental strategies. Attracting and retaining skilled talent was the most urgent Human-Centric barrier, followed closely by human-machine collaboration. Resisting change and fostering innovation further underscored the need for cultural adaptation to support I5.0 transformation. For Resilience, quantifying resilience and establishing robust risk management practices were the company's primary concerns. Challenges of adaptability and preparation for constant change were moderate compared to other resilience-related issues. For Overarching, global competitiveness, regulatory frameworks, market uncertainty, unclear economic benefits, and lack of a well-defined transition roadmap were most prominent. These factors prevent the company from aligning its strategies with I5.0 principles. Financial constraints and alignment with organizational values raised less concern.

From a managerial perspective, the HR, Logistics, and Sustainability managers were largely consistent, their assessments varying little. The most significant differences emerged in three key areas: need for employee training and development in I5.0 skills, financial constraints affecting I5.0 implementation, and customer-driven demands for I5.0 adoption. These variations stress the cross-functional nature of I5.0 and different priorities across departments.

Comparing the two companies

While both companies recognize similar barriers, their priorities differ, particularly in Sustainability. Both show similar concern for Resilience. Among key differences, Sustainability varies most in carbon footprint reduction, which Company 1 perceives as less challenging than Company 2. In Human-Centricity, Company 2 reports more significant concerns about human-machine collaboration, training, and worker empowerment. In Resilience, companies differ risk management strategies to identify and mitigate threats. Overarching concerns diverge most on financial constraints and financial feasibility.

Applying LSS tools to overcome I5.0 barriers

To achieve the fourth specific objective, the LSS manager proposed a suite of LSS tools tailored to each barrier identified. The results highlight Define, Measure, Analyze, Improve, and Control (DMAIC) (12 mentions), Value Stream Mapping (VSM) (9), and Kaizen (6), due to broad applicability in process optimization and waste reduction. Other widely referenced tools included Suppliers, Inputs, Process, Outputs, and Customers (SIPOC) (5), Failure Mode and

Effects Analysis (FMEA) (4), and Plan-Do-Check-Act (PDCA) (2), with structured approaches to problem-solving and risk assessment.

Additional tools (Poka-Yoke (2), 7+1 Wastes (1), Benchmarking (1), Brainstorming (1), Gemba Walks (1), and Hoshin Kanri (2)) were recognized for error-proofing, strategic alignment, and fostering a culture of CI.

For workforce development and change management, managers recommended Skills Matrix (1), Single-Minute Exchange of Die (1), SWOT Analysis (1), and Voice of the Customer (1) to align employee capabilities with I5.0.

To quantify risks and ensure process stability, Monte Carlo Simulation (MCS) (1), SPC (1), and Standard Work (1) were recommended. Visual Management (1) and Kotter's 8-Step Change Model integrated with LSS (1) support structured transformation.

Other relevant methodologies: Balance Scorecard (BSC) (1), A3 Problem-Solving Reports (1), Design for Six Sigma (1), and Cost-Benefit Analysis (CBA) with DMAIC (1), provided structured solutions for financial and regulatory challenges.

Proposal for applying LSS tools to overcome I5.0 barriers identified

Sustainability posed the least significant barrier to application, but improvements in waste reduction and energy efficiency remained crucial. LSS Sustainability tools include VSM and 7+1 Wastes (analyze material and energy flows, identify inefficiencies in circular economy implementation), Design for Six Sigma (optimize processes for smaller carbon footprint), SIPOC and VSM (evaluate environmental impact, integrate sustainability into operations), and DMAIC and VSM (measure and reduce carbon emissions while maintaining efficiency).

Companies can address Human-Centric barriers using Standard Work, Skills Matrix, and Visual Management (document and standardize new I5.0 skills, minimizing knowledge gaps), DMAIC (identify skill deficiencies, measure training effectiveness, establish control mechanisms to sustain workforce development), Kotter's 8-Step Change Model (foster leadership involvement, structured training, motivation strategies to ease transitions), and Gemba Walks, Kaizen Events, and Poka-Yoke (align initiatives with real employee needs and operational conditions).

Resilience was the most significant challenge, especially to mitigate disruptions and quantify organizational resilience. LSS tools suggested included FMEA (identify potential failure points and assess their impact, enabling proactive mitigation), MCS (gain probabilistic insight into resilience planning by modeling potential risks and uncertainties), BSC and SPC (track process stability over time, meet resilience KPIs), and Kaizen (facilitate structured improvement workshops, enhancing adaptability and continuous learning).

Companies' Overarching concerns were structured approaches to align I5.0 principles with business objectives. Effective tools recommended include Hoshin Kanri (ensure strategic alignment, define action plans, establish accountability); Benchmarking, SWOT Analysis, and SIPOC (evaluate industry best practices, competitive positioning, regulatory gaps); CBA in DMAIC (assess financial feasibility of I5.0 investments); and A3 Problem-Solving Reports and FMEA (create structures for regulatory compliance, corrective action planning).

IV. DISCUSSION

This section elaborates on the study's main findings, compares them to existing literature, and discusses their implications for theory and practice in I5.0 context.

A. LSS in Engineering Management

LSS is a mature methodology widely adopted across industries to enhance quality, reduce waste, and improve operational performance [10]. In engineering management, it has been instrumental in fostering efficiency and strategic alignment, but its applications traditionally stress process optimization and customer value, often neglecting broader goals like sustainability, human-centricity, and resilience. This study expands LSS's applicability by demonstrating its relevance to multidimensional barriers in I5.0 contexts.

B. Literature gaps

Limited but growing research has examined technological and organizational aspects of I5.0, but we lack integrative frameworks. Kaswan et al. [15] and [55], propose conceptual models to embed I5.0 in organizations, yet research shows limited consensus on barrier prioritization or operational guidance. We address this gap through empirical insights and structured mapping of barriers to LSS tools.

C. Expert-practitioner divergences

The Delphi panel prioritized strategic misalignment and leadership inertia, whereas academic discourse often highlights systemic concerns (ethics, employment quality). This divergence shows practitioners' focus on tangible, operational challenges vs. scholars' on broader paradigm shifts. Both views are critical and complementary in understanding I5.0 adoption.

D. Thematic findings: Barriers and solutions

To date, no comprehensive framework explicitly integrates LSS with I5.0. Our study is the first to (1) identify and prioritize barriers to I5.0 implementation using a Delphi-informed consensus process, (2) analyze perceptual differences across organizational contexts, and (3) propose a set of LSS tools directly mapped to those barriers. We thus expand LSS's traditional focus on efficiency to a broader role as strategic enabler of socio-technical innovation. This novel advance in engineering management literature aligns performance excellence with the evolving demands of sustainable, human-centered industrial systems.

***Sustainability**:* Important barriers remain in integrating Sustainability into organizational practices. We find that organizations struggle to align I5.0 adoption with sustainability policies, energy-saving goals, and circular economy. Adel [32] and Kraaijenbrink [33] similarly identify sustainability integration as a primary obstacle to widespread I5.0 adoption. Ghobakhloo et al. [54] strongly support energy efficiency, carbon footprint reduction, and waste minimization, areas in which organizations often underuse I5.0 potential.

The application of LSS tools (e.g., DMAIC, PDCA cycles) provides a structured approach for improving sustainability practices. 7+1 Wastes and VSM are also useful for overcoming barriers in circular economy adoption, especially product design for longevity and reusability. Like Cherrafi et al. [56] and Garza-Reyes [57], who value LSS methodologies' role in driving sustainable efficient industrial practices, our findings stress integrating sustainability metrics into I5.0 engineering strategies and continuously assessing environmental impact.

Human-Centricity: Human-Centricity showed barriers to talent attraction, retention, and empowerment as central to successful adoption, aligning with Ávila-Gutiérrez et al. [41] on the human-centric nature of I5.0. Our results advise workforce engagement and leadership development to overcome resistance to change and ensure employee empowerment to thrive in an I5.0 environment. This result is key to engineering management, as leaders develop talent, mentor, and foster a culture of CI and ethical responsibility. Integrating workers with machines through collaborative processes remains an important specific challenge. Organizations must ensure that human skills complement technological advances rather than replacing humans with automation [58].

Employee engagement initiatives and human factors engineering are critical components in addressing these challenges. Morandini et al. [39] similarly highlight upskilling and reskilling to prepare the workforce for I5.0 era. Change frameworks (e.g., Gemba Walks, DMAIC) further help organizations manage resistance to change, foster a culture of innovation, and improve overall employee satisfaction [59].

Resilience: Resilience (adaptability, flexibility, risk management) is essential to organizations implementing I5.0. Our results align with research stressing the need for resilient manufacturing systems to adapt to rapid technological advances and external disruption [44]. Adaptive flexible processes were considered critical to achieving resilience in an I5.0 context, particularly as organizations move towards more personalized production methods and complex supply chains [60].

LSS tools such as VSM or FMEA are essential to address resilience-related barriers. They facilitate identification of potential risks and enable organizations proactively to develop strategies to manage these risks, ensuring continuity and stability when facing unforeseen challenges [61]. BSC to quantify organizational resilience also gives organizations a comprehensive framework to measure and track progress building long-term resilience [62].

Overarching: Strategic alignment of I5.0 principles with organizational business models, values, and strategies was identified as a major barrier. Consistent with prior research, this finding highlights organizations' difficulty integrating new technologies due to misalignment with traditional business structures and cultural values [48], [63]. The results suggest aligning I5.0 with company values as crucial to a successful transition. Several tools can mitigate this challenge. VSM, SWOT, and SIPOC facilitate process alignment and link adoption of I5.0 principles closely to core business objectives.

Furthermore, uncertainty about the economic benefits and financial constraints of I5.0 adoption was significant. Kumar et al. [53] and Tallat et al. [64], similarly stress the upfront financial investment required for I5.0 adoption as deterrents. Our findings indicate, however, that CBAs in DMAIC or Kaizen help organizations evaluate potential return on investment and navigate the financial challenge of implementing I5.0.

E. Variability from stakeholders' perspective

The interviewees' responses also varied, scores ranging significantly across managerial roles. Resilience scores (4.0 (HR)–2.8 (LSS) highlight organizational stakeholders' differing priorities among dimensions of I5.0 adoption. Different departments may prioritize specific aspects of I5.0 based on their roles and objectives. Sustainability Managers may prioritize sustainability-related goals and HR Managers human-centric ones, such as talent retention and empowerment. We thus stress the importance of involving wide-ranging stakeholders when planning and implementing I5.0 strategies to address diverse organizational needs and views.

F. Variability and potential influence of LSS experience

Comparison of Company 1 (long successful history of LSS implementation) and Company 2 (no LSS experience) reveals differences in how organizations perceive and prioritize I5.0 adoption barriers. We attribute these differences to the presence or absence of an LSS culture and methodology. Company 1 probably perceives Sustainability barriers as less significant due to its LSS-driven focus on waste reduction and process optimization. Company 2 faces critical barriers in life cycle assessment, possibly reflecting absence of structured sustainability practices.

For Human-Centricity, Company 1 values training and talent retention highly, in line with its LSS-driven workforce development culture, but resistance to change is a challenge. Company 2's more varied workforce development suggests differing perceptions of training needs across management levels. Company 1 recognizes increasing overall resilience and quantifies resilience as a key barrier, reflecting its proactive approach to organizational adaptability. By leveraging LSS tools, Company 1 identifies potential risks, assesses their impact, and develops mitigation strategies. Conversely, Company 2 recognizes need for risk management processes to identify and mitigate risks and for methods to quantify overall organizational resilience. This finding suggests a need for structured risk management methodologies to enhance adaptability, preventive measures, and crisis response capabilities.

Finally, for Overarching, both companies perceive global competitiveness and regulatory frameworks as critical, but Company 1 aligns better with business models and values, possibly reflecting its LSS-driven strategic focus. The companies share challenges, but Company 1's LSS structure seems to reduce variability and improve organizational readiness for I5.0 adoption. Investing in LSS methodologies could further bridge the gap between current practices and future industrial transformation, findings align with the case study by Fani et al [65], which concludes that LSS's people-focused approach enhances I5.0 implementation.

G. Policy implications

A recurring theme in participants' interaction with interviewers is governments' and policymakers' pivotal role in facilitating I5.0 adoption. These agents must provide clear I5.0 regulatory frameworks and standards [3], [54] and financial incentives [66], invest in education and training programs to develop a skilled I5.0 workforce [67], and promote understanding of benefits to society and businesses [68]. Public-private collaboration is essential to accelerate diffusion [45].

H. Contribution to theory

The Delphi study, systematic literature review, and case studies advance theoretical understanding of I5.0 implementation barriers. First, the Delphi study highlights prioritizing barriers, revealing critical gaps in organizational strategy, sustainability alignment, human-centric integration, and resilience development. It reveals the need for theoretical models to address limited understanding of its engineering components, design principles, and intended values inherent in I5.0 adoption [69].

The systematic literature review broadened understanding of this situation, identifying barriers not mentioned by the expert panel (adaptability, stakeholder impact). This disparity highlights the importance of bridging theoretical frameworks with engineering management realities, especially in the emerging I5.0 paradigm [70].

While case study reinforced the value of empirical analysis of business contexts, the theoretical value of LSS tools' suggests that engineering managers could systematically integrate these methodologies into I5.0 models for a structured approach to address barriers and enhance practical applicability of I5.0 theories.

I. Contribution to practice

This study has significant practical value for wide-ranging stakeholders implementing and educating for I5.0. Identifying key barriers and mapping them to the appropriate LSS tools provides actionable guidance for multiple user groups. For organizations (especially engineering managers, pivotal in aligning technical practices with ethical standards and environmental stewardship), the study proposes a structure to diagnose and overcome primary obstacles to I5.0 adoption. Its practical toolkits address sustainability integration, human-centric workforce development, resilience-building, and strategic alignment. Its dual focus on operational excellence and sustainable innovation positions engineering managers as key enablers of responsible I5.0 implementation. Gdoura et al. [71] and [72], stress formulating and integrating LSS requirements in an I5.0 context starting in the early design phase to reduce the need for subsequent LSS interventions in manufacturing.

Educators and academic institutions must integrate I5.0 themes such as human-centricity, sustainability, resilience, and CI into engineering and management curricula. Practical mapping of theoretical principles onto LSS tools provides a pedagogical framework for experiential learning and case-based instruction.

For students, we highlight the skills increasingly demanded in I5.0 environments: systems thinking, process optimization, cross-functional collaboration, and ethical leadership. Growing interest in I5.0 and its potential to redefine industrial priorities creates an urgent need to map current academic discourse on these concepts to clarify their evolution and identify emerging trends [73]

Understanding the interplay between LSS and I5.0 pillars equips future professionals to lead transformation initiatives in technology-enabled, value-driven organizations. Our implications reinforce the value of a multi-stakeholder perspective in transitions to I5.0 and of structured CI methodologies to support broader societal and organizational goals.

J. Limitations and future research

While this study yields valuable insights into I5.0 adoption barriers, it has limitations. The findings—based on a two-round Delphi study, literature review, and two case studies—may limit generalizability of the results. More case studies in different industries and geographical contexts are needed to validate these findings. Further, while some LSS tools were perceived as useful for overcoming barriers, more in-depth investigation of them and of other methodologies' effectiveness is needed to address I5.0's challenges.

V. CONCLUSIONS

This study contributes to the evolving discourse on I5.0 by identifying and prioritizing key barriers to its adoption and demonstrating how LSS tools can mitigate these obstacles. In combining Delphi analysis, systematic literature review, and comparative case studies, we identify strategic misalignment, leadership inertia, and organizational resistance as among the most critical challenges firms face when implementing I5.0.

One key result is a structured barrier-to-tool mapping framework that engineering managers can apply in practice. Methodologically linking barriers to LSS tools enables organizations to move beyond theoretical aspirations and begin a structured transition toward a results-oriented I5.0 paradigm.

Comparing LSS-mature and non-LSS firms provides a valuable diagnostic for practitioners and scholars to understand organizational readiness. We expect the implications of these differences to influence decision-making in workforce training, process redesign, and leadership development. For policymakers and educators, our evidence supports design of capacity-building programs and curriculum development aligned with I5.0 principles. For academics, it expands theoretical understanding of how socio-technical innovation intersects with CI cultures.

Future research should build on these findings by exploring longitudinal adoption outcomes, testing the framework in other industries and cultural contexts, and refining the role of LSS and other structured methodologies in sustainable, human-centered industrial transformation.

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