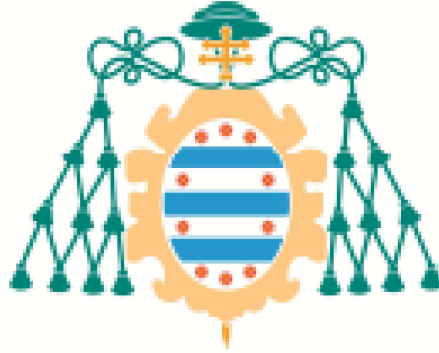




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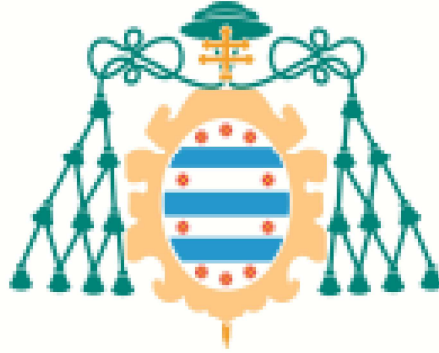
PROGRAMA OFICIAL DE DOCTORADO EN ECONOMÍA Y EMPRESA

**INTEGRACIÓN DE LEAN MANUFACTURING, INDUSTRIA 4.0 Y ECONOMÍA
CIRCULAR: EL MARCO DIGITAL GREEN LEAN PARA LA TRANSFORMACIÓN DE
LA CULTURA Y EL LIDERAZGO EN PROCESOS DE PRODUCCIÓN CONTINUA**

**INTEGRATING LEAN MANUFACTURING, INDUSTRY 4.0, AND CIRCULAR
ECONOMY: A DIGITAL GREEN LEAN FRAMEWORK FOR CULTURE AND
LEADERSHIP TRANSFORMATION IN PROCESS MANUFACTURING**

Doctorando: Ignacio Sánchez Gatell

Oviedo, abril de 2026



Universidad de Oviedo

Departamento de Administración de Empresas

PROGRAMA OFICIAL DE DOCTORADO EN ECONOMÍA Y EMPRESA

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ECONOMY: A DIGITAL GREEN LEAN FRAMEWORK FOR CULTURE AND
LEADERSHIP TRANSFORMATION IN PROCESS MANUFACTURING**

Doctorando: Ignacio Sanchez Gatell

Directora: Dra. Lucía Avella Camarero

Oviedo, abril de 2026



Universidad de Oviedo

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Año Académico: 2025/2026

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Autoriza la presentación de la tesis doctoral en cumplimiento de lo establecido en el Art. 32 del Reglamento de los Estudios de Doctorado, aprobado por el Consejo de Gobierno, en su sesión del día 20 de julio de 2018 (BOPA del 9 de agosto de 2018)

En Oviedo a 18 de abril de 2026



Universidad de Oviedo

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EN ECONOMÍA Y EMPRESA**



Universidad de Oviedo

RESOLUCIÓN DE PRESENTACIÓN DE TESIS DOCTORAL

Año Académico: 2025/2026

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Título definitivo de la Tesis		
Español/Otro Idioma: Integración de lean manufacturing, industria 4.0 y economía circular: el marco digital green lean para la transformación de la cultura y el liderazgo en procesos de producción continua		Inglés: Integrating lean manufacturing, industry 4.0, and circular economy: a digital green lean framework for culture and leadership transformation in process manufacturing
Rama de conocimiento:		
☐ Arte y Humanidades ☐ Ciencias ☐ Ciencias de la Salud ☒ Ciencias Sociales y Jurídicas ☐ Ingeniería y Arquitectura		
Señale si procede: ☒ Mención Internacional ☐ Mención Industrial ☒ Idioma de presentación de la Tesis distinto al español: INGLÉS ☐ Presentación como compendio de publicaciones		
3.- Autorización de la persona que preside la Comisión Académica		
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Resolución: La Comisión Académica del Programa de Doctorado en **Economía y Empresa** en su reunión de fecha **23 de abril de 2026**, acordó la presentación de la tesis doctoral a la Comisión de Doctorado, previa comprobación de que la tesis presentada y la documentación que la acompaña cumplen con la normativa vigente, según lo establecido en el Art.32.8 del Reglamento de los Estudios de Doctorado, aprobado por el Consejo de Gobierno, en su sesión del día 20 de julio de 2018 (BOPA del 9 de agosto de 2018)

Además, informa:

	Favorable	Desfavorable
• Mención Internacional	X	☐
• Mención Industrial	☐	☐
• Idioma: INGLÉS	X	☐
• Presentación como compendio de publicaciones	☐	☐

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Justificación

Se ha validado **POSITIVAMENTE**:

- La SOLICITUD DE AUTORIZACIÓN.
- El FORMATO de la tesis doctoral en sí mismo (cubierta/portada, impresos 009 y 010), con formato tradicional y en idioma INGLÉS. En concreto, se presenta el resumen y el apartado de conclusiones igualmente en idioma español.
- La documentación aportada para solicitar la MENCIÓN INTERNACIONAL, la solicitud de mención internacional en sí misma, la acreditación de sendas estancias internacionales de 3 y 5 meses, respetivamente, y el informe de 2 expertos internacionales ajenos a la tutorización de las estancias realizadas.
- CURRICULUM VITAE de la candidata.
- CUADERNO DE ACTIVIDADES debidamente validado por directora, tutor y coordinador del programa.
- PROPUESTA DE TRIBUNAL. La propuesta de tribunal (modelo 013bis) y las cartas de aceptación de cada miembro permiten constatar que se cumplen los requisitos establecidos para formar parte del Tribunal. En particular, todas las aportaciones señaladas por los miembros del tribunal están muy relacionadas con la temática en estudio y con sus metodologías. En todos los casos se acepta la presentación y defensa en idioma español y/e inglés y la defensa, total o parcial, en soporte online. A su vez, se ha constatado la presencia equilibrada de mujeres y hombres en la composición del Tribunal titular, así como el requisito de dos doctores pertenecientes a la Universidad de Oviedo y el hecho de que no haya más de dos miembros de la misma universidad. Por último, en relación a la mención internacional, se identifica un miembro de universidad extranjera en el tribunal titular, así como en su respectivo suplente.

En consecuencia, la Comisión Académica del Programa de Doctorado en Economía y Empresa de la Universidad de Oviedo **AUTORIZA** la presentación de la Tesis Doctoral de D. IGNACIO SÁNCHEZ GATELL en los términos descritos.

Oviedo, a 23 de abril de 2026

Presidente de la Comisión Académica del Programa de Doctorado

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Contra la presente Resolución, podrá interponer recurso de alzada ante el Rectorado, en el plazo de un mes, a partir del día siguiente al de la presente notificación, de conformidad con el art. 122 de la Ley 39/2015, de 1 de octubre, de Procedimiento Administrativo Común de las Administraciones Públicas

SR./SRA. _____
(Doctorando/a, Director/a/es/as de la Tesis Doctoral y Sra. Directora de la Escuela Internacional de Doctorado)

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RESUMEN DEL CONTENIDO DE TESIS DOCTORAL

1.- Título de la Tesis	
Español/Otro Idioma:	Inglés:
INTEGRACIÓN DE LEAN MANUFACTURING, INDUSTRIA 4.0 Y ECONOMÍA CIRCULAR: EL MARCO DIGITAL GREEN LEAN PARA LA TRANSFORMACIÓN DE LA CULTURA Y EL LIDERAZGO EN PROCESOS DE PRODUCCIÓN CONTINUA	INTEGRATING LEAN MANUFACTURING, INDUSTRY 4.0, AND CIRCULAR ECONOMY: A DIGITAL GREEN LEAN FRAMEWORK FOR CULTURE AND LEADERSHIP TRANSFORMATION IN PROCESS MANUFACTURING
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RESUMEN en español (máximo 4000 caracteres)

Las organizaciones de fabricación afrontan una necesidad de transformación compuesto: la adopción simultánea de Lean Manufacturing (LM), las tecnologías digitales de la Industria 4.0 (I4.0) y los principios de la Economía Circular (EC). A diferencia de transformaciones anteriores, que llegaron de forma secuencial, estos tres paradigmas convergen de manera concurrente, planteando exigencias específicas y, en ocasiones, contrapuestas sobre la cultura y el liderazgo organizativos. Aunque en la literatura se han analizado estos paradigmas de forma individual, y en cierta medida de forma combinada por pares, la dimensión de cultura y liderazgo asociada a su integración simultánea permanece inexplorada. Las organizaciones que intentan secuenciar estas transformaciones empezando por LM, después I4.0 y por último CE obtienen resultados sistemáticamente inferiores a los que exige el desarrollo integrado.

Esta tesis desarrolla y valida empíricamente el marco Digital Green Lean (DGL) de Cultura y Liderazgo, un modelo integrado que especifica cómo deben transformarse la Cultura Lean y el Liderazgo Lean para dar respuesta a las exigencias de I4.0 y EC en industria de producción continua. La investigación emplea un diseño híbrido de tres etapas. La Etapa 1 (publicada en *European Research on Management and Business Economics*, 2024) presenta una revisión sistemática de la literatura que identifica 19 competencias de Liderazgo Lean y 10 características de Cultura Lean, y analiza cómo I4.0 y EC afectan a cada una de ellas mediante refuerzo, modificación o la generación de nuevos requerimientos de capacidad. La Etapa 2 (publicada en *Total Quality Management and Business Excellence*, 2024) desarrolla un modelo de madurez DGL compuesto por siete dimensiones, 29 subdimensiones y 81 capacidades específicas de cultura y liderazgo distribuidas en cinco niveles de madurez, desde el nivel Reactivo hasta el nivel Forma de Vida que proporciona a las organizaciones una hoja de ruta estructurada y un instrumento de autoevaluación validado. La Etapa 3 presenta un estudio de casos cualitativo y comparativo mediante metodología Gioia que examina dos productores multinacionales de aluminio: uno con operaciones en un contexto institucional europeo orientado por la regulación y otro integrado en una iniciativa de visión nacional en Oriente Medio impulsada por el liderazgo.

Del análisis integrado emergen tres hallazgos transversales. En primer lugar, el desarrollo de capacidades DGL es intrínsecamente paralelo, no secuencial: las organizaciones que intentan secuenciar las transformaciones pierden las sinergias que su gestión simultánea genera. En segundo lugar, cuatro tensiones estructurales (eficiencia y regeneración, estandarización y



digitalización, cumplimiento normativo y ventaja competitiva, y rendimiento a corto plazo y capacidad a largo plazo) persisten en todos los niveles de madurez. Estas tensiones se gestionan, no se resuelven, y su navegación eficaz constituye una competencia de liderazgo diferencial. En tercer lugar, los contextos institucionales no solo influyen en el ritmo del desarrollo de capacidades, sino que configuran sus itinerarios. Las organizaciones Europea y de Oriente Medio desarrollaron mecanismos de desarrollo cualitativamente distintos que, sin embargo, convergieron en configuraciones de capacidades equivalentes, fenómeno que esta tesis denomina equivalencia de itinerarios institucionales, una extensión tanto de la Teoría de Capacidades Dinámicas como de la Teoría Institucional.

Teóricamente, la tesis realiza cuatro contribuciones. Caracteriza el DGL como una evolución de cuarta generación de LM. Demuestra que los sistemas LM consolidados crean condiciones habilitadoras para la adopción de la EC. Aporta la primera descripción empíricamente fundamentada de los fundamentos organizativos a través de los cuales se producen las transiciones hacia la circularidad. Y avanza en la teoría institucional documentando la influencia bidireccional entre organizaciones y sus entornos: las organizaciones más capaces configuran activamente los marcos regulatorios y normas sectoriales que condicionan su propio desarrollo.

Para los profesionales, la tesis ofrece un modelo de madurez DGL validado con herramienta de autoevaluación, directrices basadas en evidencia procedentes de organizaciones que han afrontado los retos de integración y una hoja de ruta de desarrollo estructurada y aplicable en distintos contextos institucionales.

RESUMEN en Inglés

Contemporary manufacturing organizations face a transformation imperative: the simultaneous adoption of Lean Manufacturing (LM), Industry 4.0 (I4.0), and Circular Economy (CE) principles. Unlike previous transformation waves that arrived sequentially, these three paradigms converge concurrently, each making distinct and, at times, competing demands on organizational culture and leadership. While the literature has examined these paradigms individually, and to some degree in pairwise combinations, the culture and leadership dimension of their simultaneous integration remains substantially unaddressed. Organizations that attempt to sequence these transformations (LM, I4.0 and CE) consistently fall short of the integrated capability development that simultaneous implementation requires.

This thesis develops and empirically validates the Digital Green Lean (DGL) framework for Culture and Leadership, an integrated model that specifies how Lean Culture and Lean Leadership must transform to accommodate the demands of I4.0 and CE in process manufacturing. The research employs a three-study hybrid design. Study 1 (published in *European Research on Management and Business Economics*, 2024) presents a systematic literature review that identifies 19 Lean Leadership competencies and 10 Lean Culture characteristics and analyses how I4.0 and CE affect each through capability requirements. Study 2 (published in *Total Quality Management and Business Excellence*, 2024) develops a DGL maturity model comprising seven dimensions, 29 subdimensions, and 81 specific culture and leadership capabilities distributed across five maturity levels, from Reactive to Way of Life, providing organizations with a structured pathway and a validated self-assessment instrument. Study 3 presents a comparative qualitative case study using Gioia methodology, examining two multinational aluminum producers: one operating in a European regulatory-driven context, the other embedded in a Middle Eastern leadership-driven national vision context.

Three cross-cutting findings emerge from the integrated analysis. First, the capability development required for DGL is parallel rather than sequential: organizations that attempt to stage transformations lose the synergies their simultaneous management generates. Second, four structural tensions (efficiency vs regeneration, standardization vs digitalization, compliance vs competitive advantage, and short-term performance vs long-term capability) persist across all maturity levels. These tensions are managed, not resolved, and their effective navigation constitutes a distinct leadership competency. Third, institutional contexts do not merely influence the pace of capability development; they shape its pathways. The European and Middle Eastern organizations developed qualitatively different developmental mechanisms that nevertheless converged on equivalent capability configurations, a phenomenon termed



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institutional pathway equivalence, an extension of both Dynamic Capabilities Theory and Institutional Theory.

Theoretically, the thesis makes four contributions. It characterizes DGL as a fourth-generation evolution of LM, extending the field from linear efficiency optimization into a digital-sustainable paradigm. It demonstrates that established Lean systems create enabling conditions for CE adoption rather than simply constraining it, challenging alignment assumptions. It provides the first empirically grounded account of the organizational foundations through which macro-level circularity transitions occur within manufacturing firms. And it advances institutional theory by documenting bidirectional influence between organizations and their institutional environments: the most capable organizations do not merely respond to institutional pressures; they actively shape the regulatory frameworks and industry standards that condition their own development.

For practitioners, the thesis delivers a validated DGL maturity model and self-assessment tool, evidence-based guidelines derived from organizations that have integration challenges, and a structured roadmap applicable across different institutional contexts. The research was conducted within the aluminum industry, providing sectoral specificity to the empirical validation while generating findings that are theoretically transferable to other continuous and process manufacturing contexts.

**SR. PRESIDENTE DE LA COMISIÓN ACADÉMICA DEL PROGRAMA DE DOCTORADO
EN ECONOMÍA Y EMPRESA.**

*To my parents, Nacho y Bea,
whose firm belief in education gave me the foundation for everything that followed.*

*To Eva,
whose patience transformed late nights into shared journeys, and whose love made the
impossible feel achievable.*

*To the manufacturing professionals and scholars,
who build our world and shape futures none of us could have predicted.*

ACKNOWLEDGMENTS

Manufacturing research is solitary work only on the surface. Behind every decision in this thesis there are people whose support and influence are visible to me even when it does not appear explicitly on the document. This work would not have been possible without the guidance, support, and generosity of those individuals.

Professor Lucía Avella Camarero supervised this research with a rigor and generosity that I did not always appreciate in the moment and have come to value enormously in retrospect. She challenged assumptions I brought up uncritically from twenty-five years on the shop floor, insisted on theoretical precision when practitioner instinct was pulling in a different direction, and gave me the space to pursue lines of research that looked uncertain from the outside. She also knew when to push and when to wait. Doctoral supervision at that level is a form of intellectual expertise, and I am grateful for it.

Dr. Waseem Abaza hosted my international research stay at Zayed University in Abu Dhabi and introduced me to institutional dynamics that no amount of European fieldwork would have surfaced. The conversations in Abu Dhabi changed how I read the case study data from both contexts. His understanding of Middle Eastern organizational culture and his willingness to engage seriously with the research questions I was wrestling with made the cross-regional dimension of this research genuinely possible rather than merely asserted.

My parents gave me something better than encouragement: a conviction, absorbed early and never quite questioned, that sustained attention to a difficult problem is worthwhile. Whatever patience I brought to this research, I learned from watching them. This doctoral degree is as much yours as mine, especially in these tough moments you are going through.

Eva carried more of the weight of these six years than she was ever asked to carry. She listened to ongoing arguments over dinner with more patience than they deserved, absorbed the distraction and absence that long-term research imposes at home, and never made me feel that the work was competing with something more important. It was not a small contribution. Your partnership made it meaningful.

The aluminum industry professionals who agreed to be interviewed for this research gave something genuinely valuable: honest accounts of organizational challenges that most

companies prefer to keep internal. They spoke fairly about what had worked and what had not, about pressures from above and friction from below, about the distance between corporate sustainability commitments and operational reality. Their willingness to do that, in the middle of demanding production schedules and under confidentiality constraints I respect, is what made the empirical chapters substantive rather than illustrative. I cannot name them, but the research reflects their experience on every page.

I am grateful to the University of Oviedo for providing the institutional framework and resources necessary for doctoral research, and to Zayed University for hosting my international research period.

Finally, to the colleagues working daily in manufacturing and dealing with the gap between operational excellence ambitions and the relentless pressure of production schedules. This research was written with you in mind. The problems it addresses are your problems. I hope some of it is useful.

FUNDING DECLARATION

This doctoral research was conducted without any funding support from grants, scholarships, or commercial entities. The work was undertaken independently with institutional support from the University of Oviedo for the doctoral program and from Zayed University, Abu Dhabi, for the international research period required for the International Doctorate mention.

Ignacio Sánchez-Gatell López

Oviedo, April 2026

ABSTRACT

Operational excellence through Lean Manufacturing, technological change driven by Industry 4.0 (I4.0), and sustainability through the Circular Economy (CE) are arriving simultaneously, each making distinct demands on the organizations that must implement all three. Companies today do not get to choose which transformation to address first. Each concept offers proven organizational benefits. What the management literature has not adequately addressed is the culture and leadership dimension of that convergence: how organizations must build the human and organizational capabilities to implement all three at once without sacrificing operational performance and efficiency in any of them.

This thesis develops and provides exploratory empirical corroboration for the Digital Green Lean (DGL) framework focused on Culture and Leadership, an integrated model explaining how Lean Culture and Lean Leadership must transform to accommodate I4.0 and CE demands in process manufacturing. This thesis employs a three-study hybrid research design: (1) a systematic literature review establishing the conceptual foundation; (2) a maturity model development operationalizing DGL Culture and Leadership capabilities; and (3) a comparative qualitative case study grounding the framework in organizational practice across contrasting institutional contexts.

Study 1- Conceptual foundation through a systematic literature review (Chapter 4, published in *European Research on Management and Business Economics*, 2024) identifies 19 Lean Leadership competencies and 10 Lean Culture characteristics through systematic review. It analyzes how I4.0 and CE influence each of them through reinforcement, modification or by generating new capability requirements. Study 2 - Development of the DGL Culture and Leadership maturity model (Chapter 5, published in *Total Quality Management and Business Excellence*, 2024) develops a DGL maturity model comprising seven dimensions, 29 subdimensions, and 81 specific culture and leadership related capabilities distributed across five maturity levels, ranging from Reactive to Way of Life. Study 3 - A comparative qualitative case study (Chapter 6) examines two multinational aluminum producers, one operating within European regulatory-driven institutional contexts, one within Middle Eastern leadership-driven National Vision initiatives, using Gioia methodology to identify how institutional environments shape organizational capability development pathways.

Across the three studies, a consistent finding emerges: organizations that attempt to sequence these transformations, first Lean, then digital, and finally circular, consistently fall short. The capability development required for DGL is inherently parallel rather than sequential. While institutional context significantly shapes implementation pathways, it does not determine outcomes. Organizations that engage proactively with their institutional environments, rather than responding passively, develop more comprehensive capability sets. Moreover, organizational learning and stakeholder engagement systems mediate the relationship between the integration of these concepts and sustainable performance. The research also reveals four recurring tensions, between efficiency and regeneration, standardization and digitalization, compliance and competitive advantage, and short-term performance and long-term capability, that persist even as organizations mature. These tensions are managed, not resolved, and their effective management constitutes a leadership competency in its own.

Theoretically, the thesis positions Digital Green Lean (DGL) as a fourth-generation evolution of Lean Manufacturing, moving the field into a digital-sustainable paradigm. It identifies the organizational conditions that enable circularity transitions and include digitalization within Lean manufacturers. It demonstrates how institutional environments shape capability development pathways not as constraints, but as generative forces that produce different yet equally viable organizational responses. For practitioners, the thesis provides an empirically examined self-assessment tool and a set of evidence-based guidelines derived from organizations that have confronted these integration challenges and accumulated documented experience.

Keywords: Digital Green Lean, Lean Manufacturing, Industry 4.0, Circular Economy, Lean Leadership, Lean Culture, Organizational Capabilities, Process Manufacturing, Aluminum Industry, Maturity Model, Comparative Case Study, Institutional Context, Sustainability Transitions.

RESUMEN

La excelencia operacional a través de la Fabricación Lean, el cambio tecnológico impulsado por la Industria 4.0 (I4.0) y la sostenibilidad a través de la Economía Circular (EC) están llegando de simultáneamente, y cada una de ellas exige respuestas específicas a las organizaciones que deben implementarlas las tres simultáneamente sin tener la opción de elegir qué transformación abordar primero. Cada concepto ofrece beneficios a las organizaciones demostrados por separado. Lo que la literatura de gestión de empresas no ha abordado de manera suficiente es la dimensión de liderazgo y cultura de esa convergencia: cómo deben las organizaciones desarrollar las capacidades humanas y organizativas necesarias para implementar los tres conceptos de forma simultánea sin sacrificar el rendimiento operativo ni la eficiencia en ninguna de ellas.

Esta tesis desarrolla y aporta corroboración empírica exploratoria al marco de cultura y liderazgo Digital Green Lean (DGL), un modelo integrado que explica cómo deben transformarse la Cultura Lean y el Liderazgo Lean para dar respuesta a las exigencias de I4.0 y EC en la industria de procesos. Este propósito se aborda mediante un diseño de investigación híbrido de tres etapas: (1) una revisión sistemática de la literatura que establece las bases conceptuales; (2) el desarrollo de un modelo de madurez que operacionaliza las capacidades de Cultura y Liderazgo DGL; y (3) un estudio de casos cualitativo y comparativo que fundamenta el marco en la práctica organizativa a través de contextos institucionales contrastados.

La Etapa 1 - Base conceptual mediante una revisión sistemática de la literatura (Capítulo 4, publicado en *European Research on Management and Business Economics*, 2024) identifica 19 competencias de Liderazgo Lean y 10 características de Cultura Lean mediante una revisión sistemática de la literatura. Analiza cómo I4.0 y EC afectan a cada una de ellas a través del refuerzo, la modificación y la generación de nuevos requisitos de capacidad. La Etapa 2 - Desarrollo del Modelo de madurez de Cultura y Liderazgo DGL (Capítulo 5, publicado en *Total Quality Management and Business Excellence*, 2024) desarrolla un modelo de madurez DGL compuesto por siete dimensiones, 29 subdimensiones y 81 capacidades específicas relacionadas con cultura y liderazgo, distribuidas en cinco niveles de madurez, desde el nivel Reactivo hasta el nivel Forma de Vida. La Etapa 3 - Estudio de casos cualitativo y comparativo (Capítulo 6) examina dos productores multinacionales de aluminio, uno que opera en

contextos institucionales europeos orientados por la regulación, y otro en iniciativas nacionales de visión estratégica en Oriente Medio impulsadas por el liderazgo. Se utiliza la metodología Gioia para identificar cómo los entornos institucionales configuran los itinerarios de desarrollo de capacidades organizativos.

A lo largo de las tres etapas emerge un hallazgo consistente: las organizaciones que intentan secuenciar estas transformaciones primero Lean, luego digitalización y, finalmente, circularidad, fracasan de manera sistemática y recurrente. El desarrollo de capacidades que requiere DGL es inherentemente paralelo, no secuencial. Aunque el contexto institucional influye de manera significativa en los itinerarios de implementación, no llega a determinar los resultados. Las organizaciones que se relacionan de forma proactiva con su entorno institucional, en lugar de limitarse a responder de forma reactiva, desarrollan capacidades más completas. Además, los sistemas de aprendizaje organizativo y de participación de los grupos de interés actúan como mediadores entre la integración de los tres conceptos y el desempeño sostenible. La investigación también pone de manifiesto que cuatro tensiones recurrentes, entre eficiencia y regeneración, estandarización y digitalización, cumplimiento normativo y ventaja competitiva, y rendimiento a corto plazo y capacidad a largo plazo, no desaparecen a medida que las organizaciones avanzan en su madurez. Se gestionan, no se resuelven, y gestionarlas es en sí misma una competencia de liderazgo.

Desde el punto de vista teórico, la tesis posiciona el Digital Green Lean (DGL) como una evolución de cuarta generación de la producción Lean, llevándola hacia un territorio digital y sostenible. Identifica las condiciones organizativas que permiten la transición hacia la circularidad (a través de la digitalización) de los fabricantes Lean, y demuestra cómo los entornos institucionales configuran activamente las trayectorias de desarrollo de capacidades como fuerzas generadoras que producen respuestas organizativas distintas, pero igualmente viables. Para los profesionales, la tesis ofrece una herramienta de autodiagnóstico examinada empíricamente y un conjunto de directrices basadas en evidencia, extraídas de organizaciones que han afrontado estos retos de integración y han acumulado experiencia documentada.

Palabras clave: Digital Green Lean, Fabricación Lean, Industria 4.0, Economía Circular, Liderazgo Lean, Cultura Lean, Capacidades Organizativas, Fabricación de Proceso, Industria del Aluminio, Modelo de Madurez, Estudio de Casos Comparativo, Contexto Institucional, Transiciones hacia la Sostenibilidad.

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LIST OF ABBREVIATIONS

AI - Artificial Intelligence

CDP - Carbon Disclosure Project

CE - Circular Economy

CPS - Cyber-Physical Systems

DGL - Digital Green Lean

ERMBE - European Research on Management and Business Economics (Journal)

ERP - Enterprise Resource Planning

ESG - Environmental, Social, and Governance

GCC - Gulf Cooperation Council

GHG - Greenhouse Gas

GRI - Global Reporting Initiative

I4.0 - Industry 4.0

IoT - Internet of Things

IT - Information Technology

JIT - Just-In-Time

KPI - Key Performance Indicator

KSA - Kingdom Saudi Arabia

LCA - Life Cycle Assessment

LM - Lean Manufacturing

OEE - Overall Equipment Effectiveness

PDCA - Plan-Do-Check-Act

RQ - Research Question

SLR - Systematic Literature Review

SME - Small and Medium-sized Enterprise

TCFD - Task force on Climate-related Financial Disclosures

TPM - Total Productive Maintenance

TPS - Toyota Production System

TQM - Total Quality Management

TQM&BE - Total Quality Management & Business Excellence (Journal)

UAE - United Arab Emirates

VSM - Value Stream Mapping

WIP - Work-In-Progress

NOTE ON WRITING TOOLS

The research underlying this thesis, its questions, methodology, fieldwork, analysis, and conclusions, is entirely my own work, developed over the course of these six years, including also 25+ years of direct professional experience in the industry analyzed.

I made use of AI language tools during the writing process as editorial aids, primarily to support text organization and language refinement. All content was originated, directed, reviewed, and substantially revised by me. Where AI-generated drafts were used as a starting point, they were built upon my own research materials, published papers, and empirical findings, and were subsequently rewritten to reflect my analytical voice and the specific requirements of this dissertation.

NOTE ON CHAPTERS 4, 5 & 6 (PUBLISHED OR SUBMITTED PAPERS)

Chapters 4, 5, and 6 reproduce published or submitted papers in their original format. Sections, tables and figures within these chapters follow the internal numbering of each paper (1, 2, 3...) rather than the thesis chapter numbering system.

CHAPTER 1: INTRODUCTION

1.1 RESEARCH CONTEXT AND MOTIVATION

Walk through any operational company in Europe or the Middle East and you will find the same organizational paradox playing out in real time. Lean teams are working to stabilize processes and eliminate waste. Information technology (IT) departments are installing sensors, building dashboards, and piloting predictive maintenance systems. Sustainability officers are mapping carbon flows, preparing Environmental, Social, and Governance (ESG) reports, and engaging with certification bodies to achieve a higher level of circularity. Each group is doing something genuinely useful. Almost none of them are working together. This thesis is about why that matters and what it takes to change it.

Lean Manufacturing (LM) has a decades-long track record in operational excellence (Liker, 2004; Shah & Ward, 2003; Womack et al., 1990). Industry 4.0 (I4.0) technologies are demonstrably changing production capabilities through cyber-physical systems, IoT, and data analytics (Kagermann et al., 2013). Circular Economy (CE) principles are reshaping what sustainable production means at a systems level (Geissdoerfer et al., 2017). The complication is that no organization has the luxury of addressing them separately. Competitive pressure does not pause while a company finishes its Lean maturity journey. Carbon legislation does not wait for digital infrastructure to be ready. More importantly, each concept makes distinct and sometimes conflicting demands on culture and leadership, the organizational dimensions that determine whether any transformation takes place effectively.

The research gaps this thesis addresses are specific: it does not concern the three paradigms individually, each of them has substantial literature, but rather how Lean Culture and Lean Leadership must adapt when the three are pursued simultaneously. While research on each paradigm individually is extensive, systematic investigation of how Lean Leadership and Lean Culture must transform when all three are pursued simultaneously is largely absent. That absence has real consequences. Manufacturing leaders worldwide face practical decisions about how to apply Lean discipline alongside algorithmic decision-making, how to pursue circular resource flows while maintaining process stability, and how to build the organizational culture that all three require without frameworks adequate to the task.

1.1.1 Industrial and Personal Context

Leadership and culture determine whether organizational transformations succeed or quietly fail (Mann, 2009; Seidel et al., 2019). Technical solutions such as Lean tools, I4.0 technologies, and CE practices can create conditions for success but cannot substitute for it. This conviction is not primarily theoretical. It also comes from more than 25 years in manufacturing across aluminum production, defense and technology, digital identity, and operational excellence consultancy, through roles ranging from shop floor engineer to executive.

The journey began on the shop floor of aluminum smelters, where operational excellence is learned through dealing with molten metal at 960°C, complex electrochemical processes, and the demands of continuous operation. That context teaches something that classroom training rarely does on how organizations cannot digitalize what they do not understand and cannot make circular what they cannot first make stable and predictable. Understanding how aluminum oxide dissolves in molten cryolite, how electrical current drives the reduction reaction, and how bath chemistry affects metal quality is the foundation on which everything else depends.

I have seen Lean implementations achieve genuine transformation and others fail creating confusion around digital initiatives, generating circularity commitments that remain disconnected from operations, and failing to move from basic environmental management to genuine circular practices. The pattern, repeated across different industries and contexts, is consistent. Transformations succeed when leaders develop integrated capabilities and when cultures genuinely embrace learning and adaptation. They fail when treated as technical exercises, when cultures resist change regardless of the quality of the technical solution, or when the three concepts are pursued as separate initiatives by separate organizational functions that rarely talk to each other.

Work in consultancy across diverse industries revealed both the universal principles and the sector-specific nuances of transformation. Discrete manufacturing differs from continuous processes. Consumer goods face different institutional pressures than industrial products. Capital-intensive industries carry different constraints than labor-intensive ones. In defense and technology, the fundamental challenge was how to build capabilities for change while maintaining operational stability where failure costs are extreme. A similar pattern emerged in fields such as web 3.0, blockchain, and digital identity, that are very different contexts in

which advanced technology is necessary but not sufficient; it is organizational adaptation that determines whether technical potential becomes operational reality.

Experience across Europe and the Middle East, from startups to multinationals, demonstrated that integrating Lean, I4.0, and CE requires shifts in leadership and culture, not just technical solutions. The specific implementation challenges differed by context, but the underlying leadership problem repeated consistently. The stakes are particularly high in continuous process industries with high electricity consumption, where operational decisions carry significant environmental impact and capital intensity makes transformation both critical and risky. A failed transformation in a discrete manufacturing plant may produce scrap and delay shipments. A failed transformation in an aluminum smelter can shut down production for weeks, waste months of capacity, cost hundreds of millions of dollars, and threaten hundreds of jobs.

1.1.2 The Aluminum Industry as Empirical Context

Aluminum production sits at the intersection of all three paradigms in a way that makes it an unusually productive empirical context for this research.

The industry has pioneered Lean implementation. Major producers like Alcoa, Elkem, Emirates Global Aluminium, Norsk Hydro, Qatalum and Rusal, have embedded Lean principles and productivity as core management systems for over two decades (Goshime et al., 2019). Emirates Global Aluminum defines Lean as "a business culture that enables operations and support processes to be improved by continuously eliminating wasted activity" emphasizing that "the core of LM is the philosophy that everyone can contribute to continuous improvement and Kaizen". Norsk Hydro's AMPS (Aluminum Metal Production System) represent their "common platform for continuous improvement which has been developed based on Lean principles". Similar systems exist across major producers including Rusal, Alcoa, Elkem, and Qatalum.

The continuous process nature of aluminum production makes flow optimization especially important. Metal flows continuously through smelting, casting, extrusion, and rolling operations; interruptions are costly not only in lost production but in massive energy waste and product quality degradation. A single smelter shutdown can take weeks and millions to restart. The electrochemical reduction process cannot be stopped and started like an assembly line: cells must be maintained at precise temperatures, chemical balance must be

preserved, and breaking continuous operation has consequences that compound over time. This operational reality shapes everything about how Lean, I4.0, and CE must be applied.

Aluminum is considered a commodity, and it intensifies the competitive pressure behind operational excellence. Margins are small, product differentiation is limited, and operational efficiency is becoming the most competitive differentiator. Companies that cannot match best-in-class operating costs cannot compete. This creates relentless pressure for Lean implementation and equally relentless pressure to maintain performance during any transformation.

From an I4.0 perspective, aluminum offers substantial digitalization potential driven precisely by its process characteristics. Continuous production generates vast real-time data: temperatures across hundreds of control points in reduction cells, chemical compositions measured through automated sampling, equipment vibration patterns indicating wear before failure, electrical consumption patterns showing energy efficiency, metal flow rates indicating process stability. Advanced process control, predictive maintenance, digital twins, and machine learning algorithms can extract value from this data in ways that the industry is still learning to realize. The challenge is that capital intensity is extreme, a modern smelter costs billions and operates for 30 to 50 years. Equipment built in the 1980s or 1990s was not designed for digital integration. Retrofitting legacy systems are technically complex and expensive, and the requirement for continuous operation creates justified risk aversion toward any digital system that might trigger an emergency shutdown.

Contrasting to CE clear existing definitions (Kirchherr et al., 2017), aluminum presents what might be described as aluminum's defining paradox. The material is among the most naturally circular in industrial use: aluminum recycles indefinitely without property degradation, recycling requires only 5% of the energy needed for primary production, and in regions like Europe over 75% of aluminum ever produced remains in productive use through repeated recycling. Some aluminum first produced a century ago continues circulating through the economy. This circular potential is genuinely exceptional.

Yet despite it, primary aluminum production remains one of the most energy-intensive industrial processes globally, consuming roughly 4% of total world electricity production (World Economic Forum, 2023). A single large smelter consumes as much electricity as a city with few million people. This creates a convergence of decarbonization pressure that would

be difficult enough to manage if it came from a single source. But it does not. Governments are embedding carbon reduction targets into industrial policy with real financial consequences. Reporting requirements are expanding. The capital markets have shifted: ESG criteria now shape allocation decisions in ways that affect cost of financing directly. And the largest buyers of aluminum have set procurement targets tied to carbon content, which means carbon performance is becoming a market access question, not just a reputational one. The decarbonization path is technically and economically complex, requiring renewable electricity transitions, improved process efficiency through not-yet-proven technologies such as inert anodes, a type of anode used mainly in electrolysis processes, especially in the aluminum industry, that does not get consumed during the electrochemical reaction, that have been under research for at least 25 years, increased recycling rates requiring coordination across fragmented value chains; in summary a fundamental rethinking of business models and transformation in social and economic systems (Melnik et al., 2019).

The simultaneity of operational excellence through Lean, digital transformation through I4.0, sustainability transformation through CE pressures is the central organizational challenge this thesis examines. Aluminum producers cannot address them sequentially. Competitive pressures demand operational excellence today because customers will not accept higher prices while competitors improve efficiency. Digital technologies create both opportunities and threats that must be addressed now. Decarbonization mandates have hard deadlines. European carbon border mechanisms begin phasing in soon, major customers have set procurement targets tied to carbon content, investors are making allocation decisions based on climate strategies.

The challenge is how to lead and build organizational cultures capable of integrating these concepts coherently while maintaining safe, reliable, efficient operations. Leaders cannot tell operators to focus only on Lean this year, then switch to I4.0 next year, then address CE the following year. All three must be pursued together.

1.1.3 Geographic and Institutional Context

The aluminum industry's global nature enables examining transformations across different institutional environments, adding both theoretical and practical depth and the institutional environments change intensely across regions, shaping how organizations can and must respond to transformation initiatives.

European aluminum operations face a regulatory environment that powerfully shapes transformation approaches and organizational capabilities. The European Union's Emissions Trading System (European Commission, 2025) creates direct financial incentives for carbon reduction through tradable emission permits, making carbon emissions a real cost factor in production economics. Regulations mandate environmental reporting, recyclability standards, and stakeholder accountability mechanisms. Strong labor protections and work-councils give employees formal and legally mandated voice in decisions affecting work organization, technology implementation, and operational changes. In fact, management cannot unilaterally implement major changes and must engage with employee representatives who have real authority to shape or block initiatives. Civil society organizations actively monitor environmental performance, with NGOs and political parties capable of mobilizing public opinion and legal challenges.

This regulatory-driven institutional context creates specific pressures and enables specific capabilities. Organizations face hard environmental performance requirements backed by important penalties for non-compliance. They also benefit from clear, stable rules that reduce uncertainty about requirements, policy frameworks, and mechanisms for recovering compliance costs through product pricing in markets where all competitors face similar requirements. Good intentions without verified performance data are not accepted so the stakeholders expect systematic, documented approaches. Employee involvement in decision-making is legally required, not a proactive and decided leadership style choice. These conditions shape both what capabilities organizations must develop (systematic environmental management, stakeholder engagement, transparent reporting) and the pathways through which development occurs (formal processes, documented systems, verified outcomes).

Middle Eastern aluminum operations, particularly in Gulf Cooperation Council (GCC) countries, operate in a fundamentally different institutional environment. Regulatory requirements around environmental performance are less stringent than in Europe, though evolving rapidly. However, national vision initiatives create strong governmental pressure for transformation in different directions. Saudi Vision 2030 (2025) and UAE Future Roadmap (2025) represent comprehensive national strategies for economic diversification from oil dependence, technological advancement that builds knowledge economies, and sustainability

improvements demonstrating global leadership and attracting international investment. These translate directly into corporate mandatory requirements through state ownership or significant state influence in major aluminum producers, aligning corporate strategy with national development objectives in a way that have no equivalent in Europe.

The pressure in this context comes not primarily through compliance costs and regulatory accountability but through strategic direction and national priorities. State-owned or state-backed companies serve national economic development goals together with commercial objectives, what goes beyond only maximizing shareholder returns. If national strategy emphasizes technological leadership, companies invest in I4.0 beyond what financial calculations might justify. If national strategy emphasizes sustainability to enhance international reputation and attract investment, companies pursue ambitious circular goals because doing so serves the national agenda. Cultural values emphasizing collective welfare, long-term relationships, social responsibility embedded in religious and cultural traditions, and stewardship by managing resources responsibly for future generations, shape stakeholder expectations in ways that differ in Western regulatory contexts. The concept of stewardship in Islamic tradition echoes deeply, creating moral and social requirements for environmental responsibility beyond regulatory compliance.

Stakeholder engagement in the Middle Eastern context operates through different channels. Instead of using formal works councils or NGO pressure campaigns, engagement occurs through government relationships where government officials sit on company boards and provide direct strategic guidance. Also, community leaders and religious figures shaping local opinion, through traditional consultation mechanisms (majlis) can directly raise concerns with leadership. This creates different dynamics with less public pressure, more collaborative private engagement, stronger government direction, and weaker civil society activism.

Access to heavily subsidized natural gas creates different energy structures for GCC aluminum operations. Domestic industrial gas prices in Saudi Arabia are regulated at €1.62/MMBtu in 2024, compared to approximately €10.41/MMBtu in Germany, a ratio of more than 6:1 (Hasanov et al., 2025). Translating these fuel costs into electricity generation through standard combined-cycle conversion, GCC producers access power at an estimated €20-30/MWh, while European counterparts face industrial electricity prices averaging €171/MWh for large consumers in 2023, further compounded by EU Emissions Trading System carbon costs (Study

on Energy Prices and costs, European Union, 2024). Primary aluminum smelters in the GCC, operating under long-term government supply agreements, typically secure energy at rates below even these already subsidized reference tariffs, reinforcing a structural cost advantage that fundamentally shapes the economic inertia of sustainability capital investment decisions across both regions. This changes the economic case for circularity capital investments. Energy efficiency investments that yield a 3-to-5-year return on investment in Europe may require 10–15 years to recover in the Gulf, where electricity costs are a fraction of European levels. National vision initiatives create the non-economic drivers for circularity that can be more powerful than price signals. If national strategy designates low-carbon aluminum as a strategic priority, economic payback becomes secondary.

Understanding how leadership and culture must adapt across these contrasting institutional environments provides theoretical and practical insights that single-context research cannot generate. Different environments may require fundamentally different leadership competencies and organizational capabilities. Alternatively, successful organizations in both contexts may develop similar underlying capabilities expressed through different specific practices shaped by their institutional conditions. These statements have significant implications for both multinational companies operating across institutional contexts and, as well, for policy makers: We should define if organizational capabilities are universal or contextually specific. If the role of leadership in developing the culture change initiatives is globally or locally adapted. If the policymakers seeking to promote transformation should act through context-specific interventions or transferring best practices across different contexts.

1.1.4 Theoretical Motivations and Knowledge Gaps

Lean literature has matured over three decades into a body of research documenting practices, performance impacts, success factors, implementation challenges, and boundary conditions across industries and national contexts. Leadership and culture dimensions have received increasing attention. Researchers have identified critical competencies and supporting cultural characteristics (Dombrowski & Mielke, 2014; Seidel et al., 2017) including gemba walks (going to the actual place where work happens and seeing with your own eyes rather than relying on reports), continuous improvement mindset, respect for people by recognizing employees as thinking problem-solvers, coaching and developing others to build capability throughout the organization, systematic and structured problem-solving using

methods like PDCA, and building capability over time rather than expecting instant results. In my own experience, Lean Leadership frameworks from the late 2000s were genuinely useful, but they were built for a world where the biggest disruption was a machine breakdown, not an algorithmic decision your operators cannot interrogate. In fact, many companies developed their own leadership framework but focused on the way leaders implement basic Lean tools.

Cultural characteristics supporting Lean include long-term orientation over short-term results, collectivism enabling teamwork and shared responsibility, appropriate power distance, methods to identify and expose problems, performance orientation, achievement of tangible results and empowerment, learning orientation, continuous improvement, and systematic proactive problem-solving culture (Bortolotti et al., 2015; Dorval et al., 2019).

This literature, however, developed primarily before I4.0 emerged as a practical industrial reality and before CE became a strategic imperative rather than an optional environmental commitment. Recent studies have begun exploring Lean-I4.0 and Lean-CE relationships, but systematic examination of leadership and cultural implications at the intersection of all three paradigms remains limited. The questions that matter most for organizations attempting integration have not been answered: which traditional Lean Leadership competencies remain fully relevant when I4.0 and CE are simultaneously pursued? Which requires significant modification? What new competencies emerge as essential? Do cultural characteristics that support traditional Lean (standardization, stability, incremental improvement) conflict with those needed for I4.0 adoption, or for CE transformation, or can organizations develop cultures that support all three? In my experience again, the leadership competences companies used to define were more operational related and people management than the ones required for digital or circular transformation.

The I4.0 literature has grown exponentially in recent years but remains heavily tilted toward technological concerns (Ghobakhloo et al., 2021; Pagliosa et al., 2019). Research explores which technologies to adopt (which IoT sensors, which AI algorithms, which digital twin platforms), how to integrate them with existing physical systems and legacy IT infrastructure, what technical skills are needed to implement and operate those systems, how to manage cybersecurity risks when operations are vulnerable and ultra connected, how to demonstrate return on investment for digital initiatives and justify large capital expenses, and how to scale

pilots. Leadership appears in this literature primarily in terms of executive sponsorship for digital initiatives providing resources, political support and managing employee resistance. Limited bibliography exists of how leader competencies must evolve beyond general change leadership capabilities that would apply to this major transformation.

Cultural factors are acknowledged and mention that organizations must become more data-driven basing decisions on analytics, more innovative in adopting unproven technologies, more risk-tolerant accepting failure as part of experimentation, and more collaborative breaking down functional silos. However, systematic examination of specific cultural characteristics and their relationships to I4.0 success remains limited. What specific leadership competencies enable successful I4.0 implementation in environments with strong existing operational cultures? How do those competencies interact with Lean Leadership capabilities? These questions have not been addressed adequately.

The CE literature recognizes that circular transitions require organizational and cultural changes beyond technical solutions and business model innovations. Researchers acknowledge moving from linear to circular requires new mindsets questioning fundamental assumptions about value creation and success, metrics accounting for material flows and environmental, extended time horizons valuing long-term system operational efficiency, and new stakeholder engagement capabilities incorporating diverse perspectives into decision-making (Dagilienė et al., 2025; Jiang et al., 2022). Research on what those changes are, has generated useful findings: new mindsets questioning linear assumptions, metrics accounting for material flows and environmental impacts, extended time horizons, new stakeholder engagement capabilities (Lopes de Sousa Jabbour et al., 2018).

However, most CE research typically treats organizations as entities without existing operational philosophies or deeply embedded practices as though they had no prior culture shaping what changes are possible and how they must be sequenced. How organizations already committed to Lean principles navigate circular transitions has received minimal systematic attention. Whether Lean facilitates or constrains CE adoption, how Lean capabilities must evolve to support circularity, and what tensions arise between Lean's efficiency logic and CE's systemic perspective, remain largely unexplored in the published literature.

Integration across these literature streams is particularly limited despite their clear interconnections. Some researchers explored Lean-I4.0 relationships, typically finding that Lean provides the foundation for successful I4.0 because Lean's process stability and visual management create favorable conditions for effective digital implementation (Bittencourt et al., 2020; Buer et al., 2020; Rosin et al., 2020; Sanders et al., 2016). Other scholars have examined Lean-CE connections, arguing Lean's waste elimination aligns with circular resource efficiency goals (Kurdve & Bellgran, 2021; Nadeem et al., 2019; Sasso et al., 2025; Schmitt et al., 2021). But systematic investigation of triple integration (Lean, I4.0, and CE simultaneously) is absent from the literature. The leadership and cultural dimensions of that triple integration have barely been considered. The academic literature offers well-established frameworks for Lean Leadership, emerging frameworks for digital leadership, and early frameworks for sustainability leadership; however, it provides no comprehensive framework for leading integrated Lean–digital–circular systems. By contrast, practitioners receive fragmented guidance from Lean consultants, digital transformation experts, and sustainability advisors, with no clear integration logic

1.1.5 Practical Relevance and Urgency

The timing of this research matters. I4.0 has matured beyond early hype and pilot projects to practical implementation reality. Early adopters have accumulated experience about what works and what does not. Best practices are emerging but have not yet been systematized into management frameworks that practitioners can act on. Digital transformation is no longer a future possibility to plan for but a present imperative to manage.

CE has made a similar transition, from aspirational concept to operational requirement, through converging pressures: regulatory requirements creating real compliance costs and market access barriers; investor attention as ESG (environmental, social, governance) criteria shape capital allocation with measurable consequences for cost of financing; consumer and customer expectations as sustainability becomes a purchase criterion in B2B markets; and business opportunity recognition as organizations realize circular models can create value rather than merely reduce environmental impact (recycled materials driving premiums or product-as-service models generating recurring revenue).

Manufacturing leaders face the practical consequences of these converging pressures every day. They must make investment decisions about digital technology, often involving millions

of euros with limited guidance on organizational readiness. Companies and leaders must decide if they invest in IoT sensors throughout the plant or wait until they have stronger data analytics capability. Or if they implement digital twins in all equipment or start with pilot areas. They must respond to stakeholder demands for circularity improvements while maintaining operational performance and financial results. The pressure is coming from every direction at once: customers asking for verified carbon footprints, investors scoring climate strategies before allocating capital, regulators requiring environmental reporting, and local communities watching closely. But shareholders still expect returns and workers still expect stable employment. None of these expectations have gone away; they have simply been joined by new ones that did not exist ten years ago. From an outside point of view, leaders must navigate institutional environments simultaneously enabling and constraining transformation options.

For energy-intensive industries like aluminum, decarbonization adds urgency that makes deferral increasingly costly. European carbon border adjustment mechanisms implementation will soon impose important costs through taxes on high-carbon imports creating competitive disadvantages for producers not decarbonizing. Major automotive, construction, and packaging customers have set procurement targets tied to carbon content with third-party certification requirements, making carbon performance a market access question. Investors screen climate strategies with capital allocation consequences. Social license to operate depends on demonstrated decarbonization progress. Yet the technical path to decarbonization requires fundamental transformation of operations, supply chains, and business models. Transitions that cannot be achieved through incremental efficiency improvements alone, demand organizational capabilities that most organizations are still building. Required changes include mainly transitioning to renewable electricity sources consumption, infrastructure investments and potentially relocating facilities to locations with better renewable resources. Also, from operational side changes include improving process efficiency through technology not yet commercially proven at scale (for example, inert anodes), increasing recycling rates requiring coordination across fragmented value chains and development of collection infrastructure, developing breakthrough production technologies that fundamentally change electricity consumption, and rethinking and optimizing business models from linear to circular.

Research that helps organizations lead integrated transformations by identifying essential competencies, distinguishing enabling from constraining cultural characteristics, and clarifying how institutional contexts shape what is possible, addresses problems of genuine urgency and consequence.

1.2 RESEARCH PROBLEM AND RELEVANCE

The central problem driving this research can be stated succinctly: we still lack a clear understanding of how Lean Culture and Lean Leadership must evolve to simultaneously meet the demands of Industry 4.0–driven digitalization and the requirements of the Circular Economy within Lean organizations.

1.2.1 Conceptual Challenges

The three concepts have distinct intellectual origins that generate real organizational tensions when pursued simultaneously.

Lean emerged from post-WWII Japan, specifically from Toyota's need to produce vehicles efficiently under conditions of limited capital, constrained domestic markets, and resource scarcity making Western mass production approaches impractical. Taiichi Ohno, Shigeo Shingo, and others developed a system (Liker, 2004; Toyota Motor Co., 1973; Womack et al., 1990) built around systematic waste elimination (overproduction, waiting, transportation, over-processing, inventory, motion, defects), standardization and stability for improvement, continuous incremental improvement through disciplined scientific problem-solving, and respect for people as thinking problem-solvers. The philosophy prizes simplicity: problems should be visible, variability should be eliminated, and change should be continuous but incremental.

I4.0 emerged from a very different context: early 21st century in Germany, a government strategic initiative to maintain manufacturing competitiveness against low-cost global competition and rapid technological change (Kagermann et al., 2013). It emphasizes technological sophistication through cyber-physical systems, data-driven decision-making, cyber-physical integration where intelligent factories machines communicate and self-optimize, and adaptive manufacturing capable of economical mass customization. The philosophy embraces complexity and sophisticated systems creating emergent capabilities.

Change is rapid and disruptive through technological breakthrough; transformation replaces incremental improvement.

Circular Economy has roots in ecological economics, industrial ecology, and systems thinking from the 1960s-1970s but gained traction in the past decade (Geissdoerfer et al., 2017; MacArthur, 2013). It challenges linear "take-make-dispose" industrial production models, emphasizing closed-loop systems where materials circulate rather than flow linearly, resource regeneration and restoration rather than extraction and depletion, product life extension through durability, repairability, remanufacturing and reuse, and fundamentally rethinking producer-consumer-natural system relationships.

The philosophy requires systems thinking across extended time measured in decades or product lifecycles rather than quarterly results and system-level optimization rather than individual operations. Success is measured in environmental and social outcomes alongside economic performance.

When these three systems are pursued together, structural tensions arise that no amount of good implementation management eliminates. Six tensions deserve explicit attention:

First, Lean's preference for simple, standardized, visible processes comes under pressure from I4.0's complex cyber-physical systems with complex algorithms that operate, from an operator's perspective, as black boxes. Lean values going to the gemba, where work happens, seeing directly, understanding through observation. This becomes complicated when critical process decisions occur in software that even technical specialists struggle to fully comprehend. A key question emerges: When does digital complexity enhance problem visibility, and when does it obscure it?

Second, Lean's continuous incremental improvement through disciplined problem-solving conflicts with I4.0's promise of radical digital transformation through technological breakthrough. Lean builds capability through repetitive practice of structured methods, whereas I4.0 implies wholesale process redesign enabled by digital technology. Organizations must balance disciplined adherence to standards, which is what makes continuous improvement possible with rapid adaptation to technological change that renders previous standards obsolete

Third, Lean's short term and immediate waste elimination and rapid problem-solving, with its reinforcing feedback loops of visible results, conflicts with CE's circular infrastructure investments that require long time horizons before full value is realized. Lean Cultures are trained to show results quickly and maintain momentum through visible progress. CE requires patience for system-level changes whose full benefits may take years to materialize and may accrue partly to society or future periods rather than to the implementing organization.

Fourth, I4.0 promises economical mass customization producing differentiated products as efficiently as standardized ones through flexible automation. Lean achieves efficiency through standardization. Pursuing both simultaneously requires organizational capabilities that are genuinely difficult to combine and cultural characteristics that may pull in different directions.

Fifth, Lean emphasizes process-oriented value stream optimization within defined organizational boundaries. CE requires system-level thinking across extended product lifecycles, supply chains, and ecosystem boundaries where suppliers, customers, and sometimes competitors must collaborate on material recovery. Value stream mapping traces material and information flows through single organizations or tightly coupled supply chains; CE requires understanding material flows across decades and across multiple organizations with different incentives and priorities.

Sixth, Lean's operational metrics like cycle time, defect rates, inventory turns, equipment utilization, among others, are measurable, actionable, shop-floor oriented and provide rapid feedback enabling cycles improvement. CE introduces metrics that are harder to measure and operate on longer timescales: carbon footprint requiring life-cycle assessment across complex supply chains, material circularity requiring tracking across multiple use cycles, ecosystem services that resist quantification. Organizations must determine what to measure, how to balance multiple metrics operating on different timescales, and how to prevent short-term operational metrics from crowding out longer-term sustainability indicators.

In summary, organizations cannot choose between these three systems. Competitive pressures demand operational excellence delivered by Lean, institutional pressures require the sustainability outcomes targeted by the CE, and technological change creates both opportunities and threats through I4.0 that cannot be ignored. The core question this thesis addresses is **whether and how these apparently divergent philosophies can be reconciled in practice and integrated into operational systems in ways that reinforce rather than**

contradict one another. If not, must organizations instead accept fundamental contradictions and paradoxes that can be managed through trade-offs but not resolved through integration?

1.2.2 Theoretical Gaps and Literature Fragmentation

The theoretical gaps described in Section 1.1.4 have direct consequences for what the literature can offer practitioners.

Cultural factors receive mention but lack systematic examination. The CE literature recognizes organizational and cultural changes beyond technical solutions are required (Dagilienė et al., 2025; Jiang et al., 2022; Lopes de Sousa Jabbour et al., 2018). However, research focuses on business model innovation, product design, supply chain reconfiguration, and policy frameworks. Organizational capabilities, leadership competencies, and cultural characteristics supporting circular transitions remain underexplored. Moreover, CE research typically treats organizations as a company rather than entities with existing Lean commitments.

Researchers have produced frameworks for Lean Leadership, emerging frameworks for digital leadership, and early frameworks for sustainability leadership, but no framework for leading integrated Lean-digital-circular systems. The pairwise research on Lean-I4.0 and Lean-CE relationships provides partial answers that cannot be simply combined. And because each literature stream developed largely independently, the analytical categories, constructs, and theoretical lenses differ enough that integration requires genuinely new conceptual work rather than straightforward synthesis.

The I4.0 literature has grown rapidly but tilts toward technological concerns (Ghobakhloo & Azar, 2018; Veile et al., 2019). Leadership appears primarily as sponsorship and change-management.

1.2.3 Methodological Challenges

The theoretical gaps identified in the previous section partly reflect the methodological challenges involved in studying organizational phenomena that are emerging, complex, and context dependent.

Transformations associated with I4.0 and CE illustrate these difficulties. Quantitative surveys can identify broad patterns across large samples but struggle to capture the organizational processes and contextual contingencies that determine whether transformations succeed.

Qualitative studies are typically single-context, limiting the ability to distinguish universal patterns from context-specific ones.

I4.0 implementation remains relatively immature in many organizations. While early adopters have accumulated substantial experience, broader patterns have not yet stabilized. CE transitions are even less mature, with most organizations in early stages. This immaturity limits the identification of stable patterns, validated best practices, or clearly defined success factors.

The phenomena under research also involve multiple levels (individual leaders, organizational culture, operational systems), multiple domains (technical systems, organizational structures, human behaviors), and multiple timeframes (immediate operational decisions, medium-term capability development, long-term strategic direction).

Moreover, Lean, I4.0, and CE transformations appear highly dependent on institutional context, including regulatory environments, cultural values, market structures, stakeholder configurations, and national institutional frameworks. Research on such contextually complex phenomena faces inherent challenges in developing robust theory. Because most existing studies examine single contexts, our understanding of how contextual factors shape transformation outcomes remains limited.

Taken together, these methodological challenges reinforce the need for research designs capable of capturing organizational complexity without sacrificing analytical rigor.

1.2.4 Practical Challenges in Implementation

The theoretical and methodological gaps identified in the previous sections translate directly into practical problems that manufacturing leaders face. Without clear integration frameworks, strategic confusion emerges regarding how to prioritize Lean efficiency, circular economy infrastructure investment, and I4.0 adoption. Organizations sequence these efforts in ways that miss potential synergies or pursue them simultaneously through uncoordinated initiatives that compete for the same resources and managerial attention.

Capability gaps further complicate implementation. Leaders trained in Lean may lack understanding of I4.0 or CE principles. Digital specialists may not appreciate Lean discipline. Sustainability managers may have limited awareness of production realities. As a result, organizations struggle to build integrated capabilities rather than isolated areas of expertise,

leading to communications barriers and difficulty developing solutions that span all three paradigm boundaries. Conflicting assumptions about sequencing and pacing add another layer of complexity: Lean emphasizes patient capability building; I4.0 often demands rapid adoption to avoid competitive disadvantage; and CE requires long-term commitment while facing pressure for demonstrable near-term progress

Measurement also poses a practical challenge. Lean metrics provide daily operational feedback, I4.0 benefits often materialize over months, and CE impacts require years to fully realize, making integrated performance assessment difficult within conventional management frameworks. Employees consequently receive messages that are hard to reconcile: standardize for Lean but customize for I4.0; eliminate waste immediately but invest in circular infrastructure with delayed returns; trust experience but defer to data analytics. Leaders struggle to maintain organizational stability and engagement while pursuing multifaceted change across all three paradigm dimensions simultaneously.

As a result, without clear frameworks for understanding how Lean, I4.0, and CE can be integrated, organizations risk implementing these paradigms in contradictory ways that undermine rather than reinforce one another. Resources are wasted on conflicting initiatives. Employees become confused when instructed to pursue goals that appear incompatible. Transformations stall when leaders lack guidance for decision making. Digital investments fail to deliver returns due to insufficient organizational capabilities. Sustainability initiatives remain superficial because they are not embedded in operational systems.

1.2.5 Stakeholder Relevance and Research Impact

The research problem carries direct relevance for multiple stakeholder groups. For manufacturing organizations, integrated frameworks that combine Lean, I4.0, and CE provide the conceptual coherence needed to view these three initiatives as complementary rather than competing. Clearer guidance on the competencies that matter, and on how to develop them, reduces the trial-and-error learning that current fragmented advice often forces organizations to undertake. For manufacturing leaders, the research offers insights into capability building, leadership requirements, and implementation sequencing across the three paradigms. For researchers, the thesis bridges three previously fragmented literature streams, extends organizational capabilities theory to circularity transitions, and illustrates methodological approaches suited to studying emerging and complex organizational

phenomena. For policymakers, evidence on how institutional contexts shape transformation processes supports the design of programs that account for regional and cultural variation. Finally, educators can benefit from integrated frameworks that provide structure for courses helping students understand how the three paradigms connect and what leadership capabilities the next generation will need to develop.

The convergence of practical urgency, theoretical significance, and broad stakeholder relevance underscores the importance of the research undertaken in this thesis. Organizations capable of integrating Lean, I4.0, and CE will not only secure substantial competitive advantages but will also contribute meaningfully to essential long-term societal goals.

1.3 OVERALL AIM AND RESEARCH QUESTIONS

1.3.1 Overall Research Aim

This thesis aims to **develop and provide exploratory empirical corroboration for an integrated framework, the Digital Green Lean (DGL) culture and leadership framework, that explains how Lean Culture and Lean Leadership must transform to accommodate Industry 4.0 and Circular Economy models in process manufacturing.** The thesis positions DGL as the fourth evolutionary phase of Lean Manufacturing, following the Toyota Production System, its international transfer and adaptation, and its extension into services. In this trajectory, DGL represents the next stage: expanding Lean from a focus on linear efficiency toward simultaneous digitalization and circularity. Chapter 7 develops this positioning in full.

This overall aim encompasses six interrelated objectives: (1) synthesizing insights from Lean, I4.0, and the Circular Economy into a coherent framework that identifies synergies, resolves tensions and clarifies conceptual relationships; (2) extending theories of organizational capabilities, leadership competencies, and organizational culture to explain how organizations build capabilities for integrated Lean-digital-circular operations; (3) developing assessment tools that enable capability evaluation and development planning appropriate to organizational contexts; (4) providing exploratory empirical corroboration of the DGL framework through investigation of actual organizational practice, capturing both common patterns and context-specific variations; (5) examining the influence of institutional context on implementation approaches and outcomes, distinguishing universal principles from contingencies that depend on national, sectorial or cultural environments; and (6) articulating

clear implications for theory, practice, and future research based on the integration and empirical findings.

1.3.2 Research Questions

Three primary research questions (RQs) address this aim in a coherent progression.

RQ1: What is the impact of Industry 4.0 and Circular Economy on Lean Culture and Lean Leadership?

RQ1 addresses the foundational question: what changes before building maturity frameworks or comparing institutional contexts, it is necessary to establish which Lean Culture characteristics and Lean Leadership competencies remain fully relevant in a Digital Green Lean environment, which require significant modification, and what genuinely new capabilities emerge. Addressing this question requires identifying core Lean Culture characteristics and Lean Leadership competencies, analyzing how I4.0 and CE affect each, and exploring the mechanisms through which these effects operate. This question is examined through the systematic literature presented in Chapter 4, which identified 10 Lean Culture characteristics across three dimensions and 19 Lean Leadership competencies across four categories as, analyzing I4.0 and CE impacts on each.

RQ2: How could leaders assess their competencies, attitudes, and behaviors to embrace Industry 4.0 and Circular Economy while maintaining Lean Manufacturing Excellence?

Knowing what must change is insufficient for a practitioner standing in front of a workforce on Monday morning. RQ2 therefore addresses the diagnostic question: given the changes identified in RQ1, where do organizations currently stand, and what capabilities must they develop to progress? This requires a structured maturity framework with diagnostic capability. RQ2 operationalizes the DGL concept by developing a framework for assessing and developing capabilities across maturity levels. Addressing it involves defining DGL maturity levels, specifying dimensions and subdimensions, identifying the capabilities that characterize each maturity level, creating assessment tools that enable self-evaluation, and understanding development pathways. This question is addressed in Chapter 5, which presents a maturity model comprising seven dimensions, 29 subdimensions, and 81 capabilities across five maturity levels.

RQ3: How do regional institutional contexts influence organizational capability development for Digital Green Lean, and what mechanisms enable this while maintaining operational excellence?

RQ3 moves from the conceptual to the empirical. A framework that cannot be observed in real organizational settings risks remaining purely theoretical. This question acknowledges that transformation occurs within specific institutional contexts that shape both the pressures organizations face and the resources available for responding. Industry 4.0 features in this empirical examination as the enabling infrastructure through which Circular Economy capabilities are operationalized within Lean systems, the connective layer between operational discipline and circular resource management that the DGL framework theorizes. Addressing requires examining how different institutional contexts create distinct pressures and opportunities, identifying the specific organizational capabilities that develop in response, understanding the mechanisms through which capability development occurs, and comparing across contexts to distinguish universal principles from context-specific contingencies. It also requires exploring whether the DGL framework holds against actual organizational practice. This question is addressed through the comparative case study presented in Chapter 6, which examines two multinational aluminum producers operating in European and Middle Eastern institutional contexts.

1.3.3 Relationships Among Questions

The three questions form a logical progression. RQ1 establishes what changes are required and provides the conceptual foundation for DGL. RQ2 addresses how those changes can be assessed and developed, moving from abstract understanding to practical application. RQ3 examines why particular approaches prove effective in some contexts but not others and how capabilities develop in organizational practice, grounding the framework empirically.

The integrated answers (Chapters 4-6) are synthesized in Chapter 7 to articulate the complete DGL framework, combining theoretical foundations, practical assessment capability, and empirical grounding. Clear boundaries are defined to ensure focused inquiry while acknowledging broader contexts where the findings may apply.

1.3.4 Scope and Boundaries

Several scope decisions reflect both practical constraints and strategic choices about where the research can make its strongest contribution.

First, the industry focus is process manufacturing rather than discrete manufacturing or services. Continuous operations, high capital intensity, significant energy consumption, and technical complexity shape how Lean, I4.0, and CE manifest in distinctive ways in this aluminum sector. Second, the organizational scale centers on large multinational corporations, where the resources required for sustained transformation are present and where contrasts in institutional context are most analytically productive. Third, the geographic focus on Europe and the Middle East provides institutional variation that illuminates how context shapes capability development pathways; other regional environments would require separate investigation. Fourth, the research was conducted between 2020 and 2025, capturing organizations at defined stages of their I4.0 and CE journeys. Finally, the functional focus is operations and manufacturing leadership and culture, rather than enterprise-wide transformation. Together, these boundaries define the empirical and conceptual focus of the study while establishing a clear starting point for how subsequent research may extend the work into other sectors, geographies and organizational contexts.

1.4 STRUCTURE OF THE THESIS

1.4.1 Structure

The structure follows the logic of the research questions rather than conventional thesis sequencing. Part 1 is necessarily substantial because the theoretical gap that this thesis addresses must be firmly established before it can be filled. Part 2 preserves the published papers in their original form rather than integrating them into the thesis narrative, a deliberate decision, as peer-reviewed publication carries an evidentiary weight that a rewritten summary cannot replicate. Part 3 contains the thesis's original contribution: the synthesis in Chapter 7 is not a summary of early chapters but an argument that becomes possible only after the three studies are complete. The following paragraphs provide detailed information on each of the three parts.

Part 1 (Chapters 1–3) provides the theoretical and methodological foundations. Chapter 1 establishes why the research matters, what problem it addresses, what it aims to achieve, and

how the thesis is structured. Chapter 2 develops the theoretical framework by examining the evolution and principles of Lean Manufacturing, the foundations of Lean Culture and Lean Leadership, the technologies and organizational implications of I4.0, the principles and business models of the CE, and the resulting DGL conceptualization. Chapter 3 articulates the philosophical foundations of the research design, describes the multi-method approach, details the systematic literature review methodology, explains the qualitative research design using the Gioia methodology (Gioia et al., 2013; Magnani & Gioia, 2023), and addresses quality criteria and ethical considerations.

Part 2 (Chapters 4–6) presents the three empirical studies. Chapter 4 provides the systematic literature review addressing RQ1, based on the published paper 'Impact of Industry 4.0 and Circular Economy on Lean Culture and Leadership: Assessing digital green Lean as a new concept' (Gatell & Avella, 2024b). Chapter 5 presents the maturity model development addressing RQ2, based on the published paper 'A maturity model for assessing Digital Green Lean Culture and Leadership implementation in manufacturing companies' (Gatell & Avella, 2024a). Chapter 6 presents the comparative qualitative case study addressing RQ3, examining how two multinational aluminum producers in European and Middle Eastern institutional contexts develop organizational capabilities for CE implementation within Lean manufacturing systems.

Part 3 (Chapters 7–8) synthesizes and concludes. Chapter 7 integrates findings across all three studies, articulates the theoretical contribution of the DGL framework, provides comprehensive answers to the research questions, and discusses both theoretical and practical implications. Chapter 8 summarizes the main contributions, explains theoretical advances across relevant literature streams, outlines managerial implications, acknowledges research limitations, and proposes directions for future research.

1.4.2 Supporting Materials

A consolidated bibliography covering Chapters 1, 2, 3, 7 and 8 is included in Annex A; The interview protocol used in the qualitative research is included in Annex B. Chapters 4, 5, and 6, published or publication-ready papers, retain their original bibliography as accepted or submitted.

1.4.3 Navigation and Coherence

The thesis is designed for sequential reading, which provides the fullest understanding of how the three studies build on and update each other. However, readers focused on specific questions can also navigate directly: Chapter 2 for theoretical foundations; Chapter 3 for methodology; Chapters 4, 5, and 6 for empirical studies; Chapter 7 for integration and synthesis; and Chapter 8 for contributions and conclusions. Cross-references throughout the thesis connect chapters explicitly. Chapter 7 is written to demonstrate how findings of the three studies are complementary rather than merely additive, making it the central contribution of the thesis.

NOTE: BIBLIOGRAPHY OF THE CHAPTER

The consolidated bibliography for all references cited in Chapters 1, 2, 3, 7 and 8 is included in Annex A. Chapters 4, 5, and 6 are published or publication-ready papers and therefore retain their original bibliographies as published or submitted.

CHAPTER 2: THEORETICAL FRAMEWORK

Chapter 1 identified the central problem this thesis addresses: manufacturing organizations face simultaneous pressures from Industry 4.0 (I4.0) digitalization, Circular Economy (CE) sustainability requirements, and continued confidence on Lean Manufacturing as their operational foundation. These paradigms impose distinct and sometimes conflicting demands on culture and leadership, for example Lean's pursuit of stable flow and waste elimination, I4.0's data-driven variability and experimentation, and CE's emphasis on circularity that can disrupt linear efficiency logics. While the literature documents each paradigm extensively, there is limited guidance on their joint implementation, particularly regarding how Lean Culture and Lean Leadership must adapt when digital and circular logics co-occur.

This chapter develops the theoretical foundations to address that gap. Rather than treating Lean, I4.0, and CE as independent bodies of literature reviewed in sequence, it works toward a conceptual position on their interaction, encompassing complementarities, tensions, and the organizational conditions under which one paradigm conditions or transforms the others. Sections 2.1 and 2.2 establish the Lean base with its evolution, core principles, and the leadership and cultural dimensions. Section 2.3 examines I4.0, emphasizing organizational and cultural implications often understated in technical accounts. Section 2.4 addresses CE, highlighting where its logic challenges rather than merely expanding Lean thinking. Section 2.5 integrates these strands into a Digital Green Lean (DGL) conceptualization that specifies the leadership and cultural transformations required and articulates the propositions and analytical dimensions that guide the three empirical studies in Chapters 4–6.

2.1 LEAN MANUFACTURING: EVOLUTION AND PRINCIPLES

2.1.1 Origins and Historical Development

Lean Manufacturing has its roots in the Toyota Production System (TPS), developed in post-World War II Japan. The publication of *The Machine That Changed the World* (Womack et al., 1990) gave the concept its name and translated TPS for a global management audience, catalyzing a broad shift toward improving operational productivity, process efficiency, and effectiveness (Shah & Ward, 2003). The term 'Lean' captured Toyota's central observation: the same results achieved through mass production could be delivered with substantially less (less

human effort, less manufacturing space, less investment in tooling, fewer engineering hours) while also generating fewer defects across a greater product variety. Importantly, Lean should be understood as a conceptualization and diffusion of TPS rather than a one-to-one replication of the original socio-technical system (Shah & Ward, 2003; Womack et al., 1990).

Toyota's performance made the theoretical case concrete. By 2003, Toyota had achieved annual profits of \$8.3 billion, more than the top three U.S. automakers combined (GM, Chrysler, and Ford), and increased its stock value by 24% as American manufacturers' share prices fell (Liker, 2004). It also sold more cars in the United States than Chrysler, maintained the fastest product development cycle in the automotive world at 12 months, and became the benchmark for quality, productivity, and manufacturing flexibility across the industry. Beyond outcomes, TPS's distinctive socio-technical mechanisms like just-in-time for flow and pull, jidoka for built-in quality, continuous improvement (kaizen), and systematic development of people, explain how these results were achieved and provide the foundations for Lean principles.

Historically, the diffusion of Lean evolved in evident phases. In the 1990s and early 2000s, adoption emphasized tools and techniques, highlighting the technical and process dimensions. From the mid-2000s, scholarship increasingly framed Lean as an integrated system, drawing attention to interdependencies between practices, routines, and problem-solving. In the 2010s, research expanded toward culture and leadership, reflecting the view that sustained Lean performance depends on organizational conditions that enable learning, stability, and disciplined improvement rather than on isolated tools alone.

This shift is visible in the literature on Lean Culture. A systematic review by Dorval et al. (2019), using "Lean Culture" as the search term, identified 1,066 documents, with the first published in 1991 and 61% appearing between 2013 and 2018 (peaking in 2015). The variation is commonly attributed to the limits of tool-driven implementations and the recognition that Lean's durability hinges on enabling conditions that embed problem-solving and improvement into daily work. In this perspective, tools are necessary but not sufficient; they become effective and enduring when aligned with these organizational conditions.

2.1.2 Core Principles and Philosophy

Liker's (2004) 4P model highlight Philosophy, Process, People and Partners, and Problem Solving as essential features of Toyota's management system that early Lean accounts missed:

the system is fundamentally socio-technical, with only one category devoted to processes and three devoted to human, cultural, and relational dimensions. This distinction is central because it reframes Lean not as a toolbox but as a management philosophy embedded in organizational behavior. Although the 4P model received limited attention when first published, its relevance increased significantly after 2005, in parallel with the broader shift in the literature from technical implementations toward system-level and cultural explanations of Lean success.

The principles of Lean thinking form an integrated logic and separating them hides how they operate as mutually reinforcing mechanisms.

At the center of Lean thinking is the discipline of waste elimination, or muda. The conventional seven categories identified as overproduction, waiting, transportation, over-processing, inventory, motion, and defects, describe losses that directly consume resources without creating customer value. The frequently added eighth waste, underutilized human talent, is conceptually important because it links technical performance with human capability development, reinforcing the idea that Lean's operational results depend on how people are engaged, trained, and supported.

The systematic search for waste elimination generates two strategic effects. It improves operational performance, by removing non-value-adding activities, and it cultivates a collective habit of evaluating work through the lens of customer value. These two mechanisms reinforce each other over time, strengthening Lean as both a philosophy and a system rather than a set of isolated practices.

Understanding where waste lives require seeing the whole rather than the parts. Value stream thinking shifts attention from individual operations to the complete sequence of activities required to bring a product from raw materials to the customer. This system-level perspective reveals waste that remains hidden when departments optimize independently. Value stream mapping makes the current state clear enough to redesign deliberately rather than improve gradually. From there, flow and pull provide the operational response. Where products can move through operations without interruption or batching, continuous flow eliminates the waiting and accumulation that Lean treats as waste. Where continuous flow is not achievable, pull systems and kanban ensure that upstream operations produce only what downstream operations need, replacing schedule-driven production with demand-driven response.

Standardization and continuous improvement are inseparable, though they are often taught as separate topics. Standardization is frequently misread as rigidity, like a bureaucratic insistence on doing things in one predefined way. The operational logic is the opposite: without a documented standard there is no baseline against which to detect deviation, no foundation from which to measure progress, and no way to preserve gains once they are achieved. Stability in basic conditions (equipment reliability, material availability, quality consistency) matters for the same reason: it enables systematic problem-solving rather than constant firefighting. Kaizen, the continuous improvement that builds on that stable platform, is the mechanism through which the organization develops. Incremental, disciplined application of scientific problem-solving methods treating problems as learning opportunities rather than failures, accumulates capability over time. Kaizen involves everyone. This is more than a philosophical commitment; it is an organizational design choice with direct consequences for how roles, responsibilities, and authority are structured.

Respect for people is perhaps the most misunderstood principle in Lean, and the one most frequently reduced to a slogan. It does not mean treating workers well in a generic sense. It means recognizing that frontline workers carry implicit knowledge developed through years of direct experience and that no manager or engineer has access without engaging them directly. Lean organizations develop that knowledge, involve workers in improvement, and respect their judgment. This is structurally opposed to Taylorism scientific management, where thinking and doing are separated and management holds the knowledge while workers execute instructions. In aluminum smelters, operators who have spent years reading bath chemistry through anode behavior and audible cell sounds carry knowledge that no sensor array has yet fully replicated.

Visual management and genchi genbutsu, go and see, complete the picture. Problems should be immediately visible in physical and digital management systems, with any abnormality obvious to anyone who looks, enabling rapid response before small deviations compound into larger ones. Genchi genbutsu insists that understanding comes from direct observation at the actual place where work happens, not from reports, dashboards, or other second-hand accounts. Leaders and problem-solvers must see the actual situation and base decisions on verified facts rather than filtered summaries. These two principles reinforce each other: visual

management makes the situation readable immediately; genchi genbutsu ensures that the person interpreting it is there and understands the real conditions.

2.1.3 Lean Beyond Manufacturing

Lean principles have been applied well beyond manufacturing: in healthcare to reduce waiting times and medical errors (Habidin, 2017; Long, 2003; Radcliffe et al., 2020; Sobek II, 2011); in service organizations to streamline processes and reduce cycle times (Sunder et al., 2018); in government agencies to reduce bureaucracy and improve public service delivery (Erridge & Murray, 1998; Radnor, 2010); in construction to reduce project waste and improve delivery (Bettler & Lightner, 2013; Ghosh & Burghart, 2019; Hussain et al., 2019; Johansen & Walter, 2007).

This research focuses specifically on manufacturing, particularly process manufacturing, for a straightforward reason: that is where Lean's principles have been most extensively developed and validated, and where its implications for culture and leadership are most clearly elaborated. Process manufacturing environments with their continuous operations, equipment reliability requirements, safety constraints, and technical complexity shape how Lean principles manifest in ways that make cross-sector generalization difficult. This makes them a productive and specific object of study and the most appropriate empirical context for examining cultural and leadership transformation under Lean.

2.2 LEAN CULTURE AND LEAN LEADERSHIP

Lean tools and techniques, however well designed, are insufficient for sustained Lean implementation (Liker, 2004). This is the empirical finding that the literature has converged on since approximately 2005, and it is worth stating directly before examining what culture and leadership contribute. The tools create the operational conditions in which Lean can work. Culture and leadership determine whether it does and whether it endures beyond early gains.

2.2.1 Lean Leadership: Competencies and Behaviors

Mann (2009) argues that Lean Leadership represents the missing link in Lean transformation, the element that explains why so many organizations adopt Lean tools and achieve so little. Amer and Shaw (2014) put numbers on it: implementing Lean tools accounts for roughly 20% of the effort required in Lean transformation; the remaining 80% involves changing the practices, behaviors, and mindsets of leaders.

Spear (2004) analyzed how Toyota develops leaders through direct involvement in improvement activities, emphasizing that leaders must learn by doing rather than through classroom instruction alone, a point that has obvious implications for how organizations structure leadership development. Roth (2006) argued that Lean transformation requires leadership capability distributed throughout the organization rather than concentrated at senior levels. Dombrowski and Mielke (2014) proposed 15 rules for sustainable Lean Leadership, centered on leaders modeling desired behaviors, developing problem-solving capacity in others, and creating systems that make problems visible rather than invisible.

Van Dun et al. (2017) conducted mixed-methods research identifying specific values and behaviors of effective Lean managers, finding that successful Lean leaders balance people orientation with performance orientation, a balance that is harder to maintain than either orientation alone. Seidel et al. (2017) identified Lean Leadership competencies empirically, revealing that effective Lean leaders demonstrate coaching skills, technical knowledge, commitment to continuous improvement, and ability to develop others. Their subsequent work (Seidel et al., 2019) examined how general leadership theories can inform Lean Leadership understanding, concluding that Lean Leadership represents a distinct approach that conventional leadership frameworks cannot fully capture and should therefore be treated as a differentiated construct rather than a variant of generic leadership models.

Drawing on this body of research, Lean Leadership competencies fall into four main groups: technical and process competencies, people-development competencies, system and strategic competencies, and cultural and behavioral competencies. In practice, effective Lean leaders develop them together rather than sequentially.

Technical and process competencies, like a deep understanding of Lean tools and methods, the ability to identify waste and improvement opportunities, systematic problem-solving skills, and a disciplined commitment to direct observation at the gemba, form the foundation. Leaders must understand the technical experiences of production sufficiently to engage meaningfully with shop floor employees and distinguish genuine improvement opportunities from superficial ones. Without this grounding, coaching is generic and problem-solving support is theoretical. Leaders who commanded real credibility on the floor were those who understood what they were looking at when they got there, not necessarily because they had

done the job themselves, but because they had invested enough time watching and asking that the work was not abstract to them.

People development competencies are where most conventional management frameworks fall short of what Lean requires. Coaching and mentoring, creating learning opportunities, building others' problem-solving capability rather than solving problems yourself, and demonstrating genuine respect for workers' knowledge and contributions constitute the core of this category. These define the Lean leader's primary role in a way that is genuinely counterintuitive for managers trained in traditional hierarchies. Effective Lean leaders see their job as making others more capable, not demonstrating their own capability. That shift is harder than it sounds, especially under production pressure, and it rarely occurs without structures that support deliberate leadership development rather than relying on individual disposition.

System and strategic competencies extend the leader's view beyond individual operations to value streams and system interactions. Balancing short-term results with long-term capability building, aligning improvement efforts with strategic objectives, and managing change systematically rather than reactively. Leaders who can only optimize the week are inclined to create Lean tools without Lean thinking, hitting performance targets by consuming rather than developing the organizational capability that sustained improvement requires.

Cultural and behavioral competencies are the hardest to develop and the most important. Demonstrating desired behaviors visibly, showing genuine humility and willingness to learn from the shop floor, sustaining improvement effort over time rather than in bursts of initiative, and creating psychological safety for experimentation and for honest reporting when things go wrong. Leaders cannot demand cultural values they do not believe and practice. Organizations that have tried to install Lean Culture through training programs while their leaders modeled the opposite behaviors have always failed. The culture reflects the leaders' actual behavior, not their stated intentions, a pattern repeatedly documented in empirical studies of failed Lean transformations.

2.2.2 Lean Culture: Characteristics and Dimensions

Organizational culture, defined as the shared values, beliefs, and assumptions that shape how members think and act, determines whether Lean principles are internalized or presented. Research on this question has produced consistent findings. Bortolotti et al. (2015)

demonstrated that organizational culture and 'soft' Lean practices significantly influence Lean implementation success; group-oriented cultures supporting employee involvement and empowerment correlate strongly with successful Lean outcomes. Iranmanesh et al. (2019) found that Lean Culture moderates the relationship between Lean practices and sustainable performance. Paro and Gerolamo (2017) identified specific cultural dimensions that enable Lean thinking, finding that Lean Culture emphasizes continuous improvement orientation, problem visibility, teamwork, and respect for frontline workers' knowledge.

Lean Culture comprises three major dimensions described as people orientation, performance orientation, and collective orientation, though in practice they are deeply interdependent. An organization that develops one without the others rarely sustains Lean implementation for long.

The people orientation dimension is where Lean Culture departs most visibly from conventional manufacturing cultures. Respect for people, active involvement of employees in improvement, genuine development of workers' capabilities, empowerment within standardized frameworks, and psychological safety that enables speaking up about problems without fear of consequences. In organizations where this dimension is genuinely embedded, frontline workers bring improvement ideas spontaneously, problems surface quickly because people know they will be addressed rather than penalized, and knowledge accumulates in the organization rather than walking out the door when experienced workers leave. In organizations where it is performed rather than practiced, improvement activity becomes a compliance exercise, and the cultural potential of Lean is never realized.

The performance orientation dimension provides the counterweight that stops people orientation from becoming just friendliness. Lean Culture combines genuine concern for people with an equally genuine insistence on performance with processes such as continuous improvement, disciplined problem-solving, customer value orientation, measurement and data-driven decision-making, and uncompromising standards for quality. The focus is on root cause analysis and systematic resolution rather than blame, which makes problem visibility possible: people can surface problems without fearing they will be held personally responsible for circumstances often beyond their individual control. This combination of high expectations and psychological safety is what makes Lean Culture productive rather than merely pleasant.

The collective orientation dimension reflects Lean's fundamental orientation toward system performance rather than individual heroes. Teamwork and collaboration across organizational boundaries, shared responsibility for outcomes, collective problem-solving that draws on diverse experience, long-term orientation that resists short-term financial pressure, and systems thinking that evaluates decisions based on the system rather than the subprocesses. These characteristics distinguish Lean Culture from performance culture that achieve results through individual competition and short-term incentives. Lean rewards collective achievement. Organizations that maintain individual ranking systems, performance reviews, or strong functional silos alongside Lean programs typically find that the cultural infrastructure undermines the operational aspirations.

2.3 INDUSTRY 4.0: TECHNOLOGIES AND ORGANIZATIONAL IMPLICATIONS

2.3.1 Origins and Evolution

The Fourth Industrial Revolution emerged from the systematic application and integration of digital technologies in industry. The concept originated in Germany in 2011 through a government initiative formalized by Kagermann et al. (2013) and represented a significant shift in how industrial change was conceptualized: for the first time, a major industrial transition was being evaluated and planned a priori rather than recognized ex-post (Sato Duarte et al., 2018).

The expected outcome of I4.0 is the Smart Factory, where Cyber-Physical Systems (CPS), the Internet of Things (IoT), blockchain, and big data serve as foundational technologies for achieving productivity objectives (Melnik et al., 2019). In the past 30 years, each dollar invested in digital technology has generated \$20 in GDP growth, compared to only \$3 for non-digital investment, and digital technologies are projected to account for 24.3% of global GDP by 2025 (World Economic Forum, 2019).

Pardi et al. (2020) offer a useful corrective to the more enthusiastic accounts, suggesting that I4.0 may be generating expectations that organizations cannot meet, raising the risk that the concept functions as a management fashion rather than a genuinely transformative paradigm. This skepticism is worth keeping in mind. Technological potential and organizational reality are not the same thing, and social, human, and cultural factors ultimately determine whether digital technologies deliver their promised returns.

2.3.2 Core Technologies

IIoT comprises a broad range of technologies and tools that together enable smart manufacturing (Jankowska et al., 2021; Kagermann et al., 2013). Understanding them individually is less important than understanding how they interact, though a brief account of each is necessary to ground the organizational analysis that follows.

The Internet of Things (IoT) and associated sensor technologies enable connectivity between physical objects and digital systems, providing real-time data on equipment conditions, environmental parameters, product characteristics, and process variables. Cyber-Physical Systems (CPS) integrate physical processes with digital computation and networking, enabling machines to monitor processes, create virtual representations of physical reality, and make decentralized decisions so that production systems become, in principle, intelligent and self-optimizing. In continuous process industries, retrofitting legacy (e.g., 1980s) control systems for IoT integration is fundamentally different from greenfield sensor deployment; much of the IIoT adoption literature implicitly assumes the latter.

Big Data and Analytics provide the means to process the volumes of data that sensors and systems generate, extracting insights, identifying patterns, predicting failures, and optimizing performance. Cloud Computing delivers scalable computing resources that make these capabilities accessible without prohibitive capital investment, enabling collaboration across sites and lowering barriers for smaller organizations. Digital Twins create virtual replicas of physical assets, processes, or systems, supporting simulation, testing, and optimization before changes are implemented physically. Digital Twins receive considerable attention in literature and in vendor marketing, yet in continuous process industries the gap between concept and robust industrial implementation remains wider than most accounts acknowledge.

Artificial Intelligence and Machine Learning enable systems to learn from data and improve performance without explicit programming, with applications spanning quality inspection, predictive maintenance, demand forecasting, and process optimization. Robotics and Automation, including collaborative robots (cobots) designed to work alongside rather than instead of humans, extend automation into tasks that previously required human expertise or judgment. Additive Manufacturing enables complex geometries, customized products, and on-demand production that reduce tooling requirements and enable distributed manufacturing. Augmented Reality overlays digital information on physical environments,

supporting maintenance, training, quality inspection, and remote assistance. While Artificial Intelligence is experiencing a pronounced hype cycle and warrants dedicated investigation, a comprehensive treatment lies beyond the scope of this thesis.

2.3.3 I4.0 and Lean Manufacturing: Synergies and Tensions

The relationship between I4.0 and Lean is more complicated than early enthusiasm suggested. Sanders et al. (2016) argue that I4.0 research activities function as enablers for Lean manufacturing and many I4.0 technologies directly support Lean principles. IoT improves flow visibility, analytics supports problem-solving, and automation can eliminate waste. Bittencourt et al. (2020) found that Lean thinking can productively guide I4.0 implementation by providing principles for identifying value, eliminating waste, and improving continuously. Buer et al. (2020, 2018) mapped the link between I4.0 and Lean systematically, identifying complementarities alongside potential contradictions. Ciano et al. (2020) demonstrated through case studies that specific I4.0 technologies enhance specific Lean practices: IoT sensors improve visual management, predictive analytics enhance total productive maintenance, and simulation supports standardized work development.

But tensions are real and should not be minimized. Rosin et al. (2020) showed that while some I4.0 technologies reinforce Lean principles, others may contradict them. The complexity introduced by sophisticated systems can hide problems rather than make them visible, which is the opposite of what Lean requires. Data-driven decision-making may systematically undervalue frontline judgment and tacit knowledge that Lean treats as organizational assets. Over-automation can also displace the human involvement in improvement activities through which organizational learning capability is built.

The organizational and cultural implications have received less attention than the technical integration questions. Kandler et al. (2020) note that rigid hierarchical structures are still the norm in many manufacturing organizations and directly oppose the decentralization that I4.0 requires. Agile, team-based structures and dynamic management systems (e.g., short-interval control, daily management) are often necessary to realize I4.0's potential. What should those structures look like in organizations that also maintain Lean disciplines or how to balance decentralization with standardization, have not been well addressed in the literature.

2.3.4 Organizational and Leadership Implications

I4.0 adoption faces challenges that technical implementation cannot resolve. Veile et al. (2019) identified critical factors including the development of I4.0-specific knowledge, securing financial resources for sustained investment, integrating employees into implementation processes from the start, and establishing organizational cultures open enough to embrace the uncertainty that genuine digital transformation involves. Ghobakhloo et al. (2021) make the point directly: realizing I4.0's potential requires addressing organizational and human factors, not just deploying technology.

The skills question extends beyond technical training. Philip et al. (2023) identified key leadership competencies for digital transformation through a cross-sectoral Delphi study, finding that digital transformation requires leaders who can navigate ambiguity, foster innovation, develop digital mindsets in others, and manage cultural change. These are not software skills. They are organizational leadership capabilities that most Lean management development programs do not systematically address.

Two further challenges are worth naming explicitly. First, the risk of job displacement as automation expands requires organizations to manage workforce transitions thoughtfully, balancing productivity objectives against social responsibility in ways that affect both organizational culture and external legitimacy. Second, cultural resistance: managers and workers comfortable with traditional approaches may resist data-driven decision-making, algorithmic optimization, and autonomous systems, not from ignorance but from legitimate concerns about what happens to human judgment and accountability when algorithms make decisions. These concerns should be treated as design requirements for governance, transparency, and escalation mechanisms, not as a communications issue.

The gap that remains in the literature, and that this thesis addresses directly, concerns how organizational culture and Lean Leadership competencies must evolve to support I4.0 adoption without sacrificing what makes Lean effective. The specific challenge is to balance technological sophistication with operational simplicity, algorithmic decision-making with shop floor worker judgment, and the pace of digital transformation with the continuous improvement discipline that Lean Cultures require.

2.4 CIRCULAR ECONOMY: PRINCIPLES AND BUSINESS MODELS

2.4.1 Foundations and Development

Circular Economy has intellectual roots in ecological economics, industrial ecology, and systems thinking from the 1960s and 1970s, but gained mainstream organizational traction primarily in the past decade. The Ellen MacArthur Foundation's advocacy was central to that shift, commonly defining CE as a set of industrial strategies for waste prevention, local job creation, efficient resource use, and the dematerialization of industrial production (MacArthur, 2013). At its core, CE proposes an industrial economy that is intentionally restorative or regenerative by design.

Geissdoerfer et al. (2017) examined whether CE constitutes a new sustainability paradigm or a repackaging of existing ideas, concluding that while CE shares objectives with sustainable development, it offers a distinctive emphasis on closing material loops and designing out waste from the start. Modern CE thinking seeks to lower the material intensity of economic systems toward the carrying capacity of planetary ecosystems through reuse, recycling, and remanufacturing, not as end-of-pipe waste management but as fundamental principles of design (Melnik et al., 2019). Acerbi and Taisch (2020) tracked CE's evolution from broader concept to Circular Manufacturing as its principles have been applied specifically to manufacturing contexts, noting both rising interest and persistent, often underestimated, implementation challenges.

2.4.2 Core Principles and Operational Approaches

CE principles challenge linear 'take-make-dispose' industrial models at a structural level, and it is worth being clear that this is not simply a more ambitious version of conventional environmental management. The difference is architectural rather than incremental.

The most fundamental CE principle is designing out waste and pollution before it is generated rather than managing it afterward. Products should be designed for durability, repairability, disassembly, and recycling from the outset; processes should minimize material loss, energy consumption, and emissions as design requirements, not as afterthoughts addressed by end-of-pipe treatment. In the aluminum industry, this means rethinking anode consumption, bath chemistry loss, dross generation, and potlining disposal as design problems rather than operational issues. From a CE perspective, much of what is currently treated as unavoidable

waste in primary aluminum production reflects engineering challenges that have not yet been adequately prioritized.

Closely related is the principle of keeping products and materials in use as long as possible through maintenance, repair, reuse, refurbishment, remanufacturing, and recycling. This is structurally different from linear models where products become waste after single use or at end of initial service life. Economics are compelling in theory, keeping embedded value in the material system rather than discarding it, but the operational infrastructure required to realize that value is more complex than most organizations acknowledge when they first engage with CE. Reverse logistics, variable quality in recovered materials, and the organizational challenge of extending manufacturer responsibility beyond the point of sale all create real friction that circular ambition cannot resolve.

The regeneration principle is where CE diverges most sharply from conventional environmental management. Beyond minimizing harm, CE seeks to actively restore and regenerate natural capital: returning biological nutrients to productive cycles, using renewable energy, designing industrial processes that support rather than degrading ecosystems. For energy-intensive industries like aluminum, this implies rethinking not only how energy is used but also where it comes from, not simply committing to reducing emissions per ton of metal produced.

The efficiency principles concern how materials circulate once in use. CE prioritizes tighter loops (reuse, repair, refurbishment) over broader loops such as recycling or energy recovery, because tighter loops preserve more embedded value with less energy and processing. Recycling aluminum requires only 5% of the energy needed for primary production, making it one of the most favorable examples of circular efficiency in any industry. But even that figure understates what is possible if materials are kept in higher value uses longer before reaching the recycler. Material productivity, meaning extracting more value from each unit of material through design for longevity, product-service systems, sharing platforms, and cascading use, is the operational expression of that preference for inner circle loops.

What is often underestimated in CE literature is how demanding these principles are when they encounter established Lean organizations. Lean has spent decades developing stability, standardization, and efficiency within defined operational boundaries. CE requires those boundaries to expand dramatically, accepting complexity and variability in the service of

system-level sustainability. That expansion is an organizational and cultural challenge, which is precisely what this thesis addresses.

2.4.3 CE and Lean: Synergies and Tensions

At first glance, CE and Lean appear complementary. Both emphasize waste elimination (though defining waste differently), both value continuous improvement, both require systems thinking, and both ultimately seek to create more value from fewer inputs. Nadeem et al. (2019) articulate these complementarities, and they are genuine. Lean's respect for resources resonates with CE's resource stewardship. Lean's systematic problem-solving methodology can be applied to circular implementation challenges.

The tensions, however, are structural rather than incidental. Lean traditionally optimizes within existing system boundaries, making current processes better. CE requires expanding those boundaries to consider entire product lifecycles, supply chains, and end-of-life recovery systems. Lean logic tends to treat reverse logistics, disassembly operations, or variable recycled material quality as complexity to be eliminated. CE treats these as necessary design features of sustainable systems that organizations must learn to accommodate. Lean metrics measure operational efficiency in cost, time, and quality terms. CE requires accounting for environmental and social outcomes that do not translate directly into those metrics, and that may require short-term operational cost increases to deliver long-term environmental and strategic returns. This creates a fundamental tension between local operational efficiency (Lean) and system-level sustainability (CE).

Research on organizational capabilities for CE implementation confirms that successful transitions require systems thinking capacity, cross-organizational collaboration, innovation orientation, and long-term strategic perspective (Chiappetta Jabbour et al., 2019). The specific leadership competencies and cultural characteristics particularly in continuous process industries where operational excellence traditions are deeply embedded remain underexplored. That gap is part of what this thesis addresses.

2.5 DIGITAL GREEN LEAN: TOWARDS AN INTEGRATED FRAMEWORK

2.5.1 The Need for Integration

Sections 2.1 through 2.4 have established that Lean Manufacturing, I4.0, and CE each represent demanding concepts with distinct origins, philosophies, and organizational

requirements. Each offers clear operational benefits. Each also makes specific and sometimes conflicting demands on culture and leadership. The management challenge is not to choose among them: market competition demands operational excellence, technological change requires digital capability, and environmental pressures increasingly mandate circular approaches. Organizations must pursue all three simultaneously and do so in a way that avoids sub-optimizing any one through the others.

The literature does not provide adequate guidance for doing so. Research examining pairwise relationships (Lean and I4.0, Lean and CE, I4.0 and CE) has produced useful findings on complementarities and tensions within each pair. However, studies that address the joint pursuit of all three are scarce and fragmented. This absence constitutes a clear theoretical and practical gap, and it is precisely this gap that this thesis addresses.

2.5.2 Conceptualizing Digital Green Lean

Digital Green Lean (DGL) represents the synthesis of these three paradigms, with particular focus on how organizational culture and leadership must evolve to support their integration (Gatell & Avella, 2024b). The concept emerged from recognition that technical integration, connecting I4.0 systems with Lean operations and CE material flows, is necessary but insufficient. Organizational capabilities, specifically cultural characteristics and leadership competencies, determine whether integration succeeds or remains superficial and symbolic.

DGL builds upon Lean's operational excellence foundation while explicitly extending that foundation to accommodate digital technologies and circular principles. It recognizes that I4.0 technologies enable both Lean optimization and circular innovation but require leadership capable of guiding appropriate technology adoption and the organizational adaptation it demands. It also accepts that CE requirements need to expand traditional operational boundaries while preserving the operational discipline and efficiency that Lean organizations have built.

The DGL framework asks a specific question: how must Lean cultural characteristics and Lean Leadership competencies transform when I4.0 and CE are simultaneously pursued? Some traditional Lean elements remain relevant and should be preserved. Others require significant adaptation. In addition, new capabilities emerge as essential (e.g., data governance literacy, cross-boundary coordination for reverse flows, and socio-technical change management) that are not fully specified in the Lean, I4.0, or CE literatures individually. Determining which

capabilities are required and how to develop them is the core contribution of the three empirical studies presented in Chapters 4, 5, and 6.

2.5.3 Key Integration Challenges

Based on the theoretical foundations developed in this chapter, several integration challenges can be anticipated when Lean, I4.0, and CE are pursued simultaneously. These are not simply implementation problems with known solutions; there are five structural and theoretical tensions arising from the different logics embedded in each paradigm. Chapter 7 will return to them with empirical evidence from the three studies, testing which proved most consequential in practice.

Building on the six conceptual tensions introduced in Section 1.2.1, this section consolidates and refines them into five structural tensions for analytical purposes: two of those tensions named as standardization versus mass customization and the conflict between operational and sustainability metrics, are treated here as expressions of the broader standardization-versus-digitalization and efficiency-versus-circularity tensions respectively, which captures their shared logic more precisely.

Firstly, the tension process visibility versus algorithmic opacity is what makes the adoption of I4.0 difficult in lean organizations. Lean is built on the principle that problems should be visible and simple enough for frontline workers to identify and address, and immediate problem response depends on that visibility. I4.0 involves sophisticated cyber-physical systems with complex algorithms and data flows that can, from an operator's perspective, function as black boxes: the system produces an output, but the reasoning is hidden. How organizations maintain Lean's problem-visibility discipline while leveraging I4.0's analytical power, and what leadership competencies are required to navigate that balance, remains poorly understood in literature. In practice, it comes down to whether leaders understand both well enough to decide when to trust the algorithm and when to override it.

Secondly, standardization and digitalization pull in opposite directions in ways that create genuine organizational difficulty. Lean relies on standardization as the foundation for improvement because without a stable standard, there is no baseline, no deviation detection, no improvement measurement. I4.0 promises economical mass customization and adaptive production that can appear to conflict with the process stability Lean standardization requires. CE adds further complexity by introducing variable input streams through recycled materials

and closed-loop supply chains that do not behave with the consistency that Lean systems prefer. The cultural characteristics and leadership behaviors required to strike a productive balance among these three orientations remain undertheorized.

Thirdly, the incremental improvement versus transformative change embedded in each paradigm creates its own tension. Lean's DNA is continuously incremental improvement through disciplined scientific problem-solving. I4.0 involves transformative digital change at a pace and scale that incremental methods cannot manage; organizations that wait until they fully understand a technology before adopting it risk being outpaced by competitors who learn by doing. CE requires rethinking product design and business models at a fundamental level that cannot be achieved through kaizen alone. Organizations must maintain continuous improvement capability while simultaneously pursuing two forms of transformation that exceed Lean's traditional tempo. The leadership approaches that enable all three simultaneously are not well established in either research or practice.

Fourthly, the efficiency versus circularity tension is the most structurally fundamental of the five. Lean optimizes within existing system boundaries, pursuing efficiency in cost, time, and quality terms as defined by current operations. CE requires expanding those boundaries to consider full product lifecycles, closed material loops, and ecosystem impacts. A Lean manager looking at reverse logistics will see complexity, variability, and cost. A CE designer looking at the same activity will see embedded value that the linear system is throwing away. Both are right within their own frame. The leadership challenge is to hold both frames simultaneously and to make decisions that support long-term system performance without undermining the operational discipline that enables short-term performance.

Finally, the relationship between human judgment and algorithmic decision-making deserves explicit attention. Lean places significant weight on frontline workers' implicit knowledge and problem-solving capability, treating these as organizational assets that management's job is to develop. I4.0 enables data-driven, algorithmic optimization that can systematically displace human judgment rather than complement it. Organizations that fully automate decisions they once made through gemba observation and collective problem-solving may find that the organizational learning capability they relied on has quietly atrophied. The leadership competencies required to keep human judgment and algorithmic capability working together

productively, rather than one replacing the other, are central to effective DGL implementation and remain insufficiently specified in current research.

2.6 CHAPTER SUMMARY

The three concepts examined in this chapter arrive at manufacturing organizations from very different directions. Lean Manufacturing came out of post-war Japanese industrial necessity, refined over decades into a management system whose real power was always less in its tools than in the organizational conditions that determine whether those tools become embedded or remain superficial. Industry 4.0 came from a government strategic initiative in early 21st century Germany, carrying the promise of intelligent, self-optimizing production and the organizational reality that most companies are not yet equipped to deliver it at scale. Circular Economy came from ecological economics and systems thinking that industrial organizations ignored for decades, and is now arriving as a regulatory, market, and strategic imperative that cannot be deferred regardless of operational readiness.

What the chapter establishes is not simply that these three concepts coexist in the organizational environment. They make genuinely conflicting demands on culture and leadership when pursued simultaneously. The conflicts are not misunderstandings to be resolved through better communication or cleaner implementation plans. They are structural: Lean's preference for visible simplicity runs against I4.0's algorithmic opacity; Lean's standardization logic runs against I4.0's customization promise and CE's variable recovered material streams; Lean's incremental improvement pace runs against the transformative speed both I4.0 and CE require; Lean's efficiency orientation within defined boundaries runs against CE's insistence on expanding those boundaries to serve system-level sustainability; and Lean's investment in human judgment runs against I4.0's tendency to displace it with algorithmic decision-making.

Of these five tensions, this thesis argues that the one related to efficiency versus circularity conflict is the most consequential in practice because it operates at the level of what organizations fundamentally measure and reward. A Lean performance system optimized for cost, time, and quality within existing boundaries will consistently undermine circular investments whose returns accrue at the system level, over longer timescales, and partly to stakeholders outside the organization. Resolving that tension requires changes to

measurement systems, incentive structures, and strategic framing that go well beyond adding a sustainability officer to the leadership team or launching isolated circularity pilots.

The DGL concept developed in Section 2.5 brings these threads together by focusing on where the existing literature is weak: the organizational conditions, leadership competencies and cultural characteristics, that determine whether integration succeeds or remains siloed. The three empirical studies in Chapters 4, 5, and 6 investigate those conditions directly, building from conceptual foundations established here through their operationalization in a maturity framework and to empirical grounding in organizational practice. Chapter 7 returns to the integration challenges identified in this chapter with evidence from across all three studies, examining which proved most consequential and what that reveals about the nature of DGL integration in real organizations. Chapter 3 explains the methodological choices made to generate that evidence.

NOTE: BIBLIOGRAPHY OF THIS CHAPTER

The consolidated bibliography for all references cited in Chapters 1, 2, 3, 7 and 8 is included in Annex A. Chapters 4, 5, and 6 are published or publication ready papers and therefore retain their original bibliographies as published or submitted.

CHAPTER 3: RESEARCH METHODOLOGY

Chapter 2 developed the theoretical foundations for Digital Green Lean (DGL), establishing how Lean Manufacturing, Industry 4.0 (I4.0), and Circular Economy (CE) have evolved individually and what their simultaneous integration demands organizationally. The analytical distinctions drawn there between technical and cultural dimensions, between pairwise and three-way integration, and between capabilities already present and capabilities yet to be built, provide the conceptual categories through which the empirical findings will be interpreted.

The chapter now articulates and justifies the methodological approach used to address the three Research Questions (RQ). The structure follows the logic of the research design itself: first, philosophical foundations (Section 3.1), because the methodology cannot be evaluated independently of its underlying assumptions; second, the overall design (Section 3.2), because understanding how the three distinct studies combine is essential before examining any of them in isolation; then the specific methodology of each study specifically, the systematic literature review-SLR (Section 3.3), the maturity model design (Section 3.4), and the qualitative case study (Section 3.5); and finally, with the quality criteria and ethical considerations applicable across all three studies (Section 3.6).

The multi-method design described here is not simply a pragmatic accommodation to the complexity of the research questions; it reflects a considered epistemological position that different forms of knowledge require different forms of inquiry.

3.1 PHILOSOPHICAL FOUNDATIONS

Methodological choices do not exist independently of philosophical commitments. The selection of methods, the interpretation of findings, and the nature of knowledge claims, all rest on assumptions about what exists and how it can be known. Making those assumptions explicit enables the research design to be evaluated on its own terms rather than against criteria rooted in a different philosophical tradition.

Philosophical positioning involves two connected elements: ontology (what exists and what is its nature) and epistemology (how we can know about what exists). Ontology precedes

epistemology: this chapter therefore establishes first the assumptions about the nature of reality, before determining how that reality can be studied. This thesis presents ontological assumptions first (Section 3.1.1), followed by the epistemological stance that builds on those assumptions (Section 3.1.2).

3.1.1 Ontological Assumptions

This research adopts a moderate realist ontological position (Bhaskar, 2013). Organizational phenomena, including leadership behaviors, cultural characteristics, and capability development processes exist independently of the researcher's observation, yet are simultaneously socially constructed, shaped by institutional contexts, and subject to interpretation. Organizations navigate complex environments that produce discernible patterns without producing the universal regularities characteristic of natural-science inquiry.

The position has direct methodological consequences. It means this thesis does not seek to establish causal laws or generalize findings statistically across populations. Instead, the aim is to develop conceptual frameworks that represent the structure of organizational phenomena with sufficient accuracy to inform understanding and action. These frameworks hold in the contexts studied and can transfer with appropriate adaptation to meet stakeholders' needs to related contexts. The systematic literature review identifies patterns in existing research; the maturity model translates those patterns into a structured developmental framework whose validity is assessed pragmatically by its fitness for organizational diagnosis and development; the case studies reveal how patterns manifest in specific, contextually rich settings.

3.1.2 Epistemological Positioning

The thesis adopts a pragmatist epistemological stance. Pragmatism, articulated by Dewey (1929) and developed by contemporary scholars such as Saunders et al. (2019), does not privilege either positivist or interpretivist traditions, it evaluates methodological approaches according to how effectively they address the research questions at hand. Knowledge is understood as situated, constructed through interaction between researcher and phenomenon, and oriented toward both theoretical understanding and practical relevance.

Three features of the research make this stance appropriate. First, the RQs operate at different levels of abstraction that resist a single methodological approach: RQ1 asks what changes are conceptually required, a question connected to systematic literature synthesis;

RQ2 asks how those changes can be assessed and managed, a question requiring framework construction; RQ3 asks why certain approaches work in certain contexts, a question demanding interpretive depth. A rigid commitment to either positivism or interpretivism would therefore constrain the methodological selection needed to address this range.

Second, the research serves both theoretical and practical purposes. The DGL framework advances scholarly understanding while providing actionable guidance for manufacturing organizations. Pragmatism explicitly rejects the assumption that theoretical rigor and practical relevance are in tension (Goldkuhl, 2012; Johnson & Onwuegbuzie, 2004), a rejection that is not merely philosophical but directly shapes what counts here as a satisfactory research contribution.

Third, the multi-method design that pragmatism enables allows different methods to serve genuinely different purposes within a unified investigation, rather than treating methodological pluralism as a concession. The systematic literature review generates conceptual understanding; the maturity model development operationalizes it; the qualitative case studies test and extend it empirically. Each method therefore contributes a form of knowledge that the others cannot produce.

3.2 OVERALL RESEARCH DESIGN

3.2.1 Design Logic

The thesis employs a multi-method research design comprising three distinct but conceptually sequential studies. The logic follows a progression from conceptual foundation through operationalization to empirical grounding: Study 1 establishes what DGL requires of culture and leadership; Study 2 translates those requirements into a structured assessment and development framework; Study 3 examines how organizations develop the relevant capabilities in different institutional contexts. Each study builds cumulatively on the findings of the preceding one, and each generates a form of knowledge that the others are not designed to produce.

The design is not a collection of three parallel investigations conducted under the same research umbrella. Its dependencies are explicit and structural: the maturity-model dimensions in Study 2 derive from the competency and characteristic analysis in Study 1; the

capability categories examined in Study 3 are informed by both. Table 3.1 summarizes the three studies and their relationships.

Dimension	Study 1	Study 2	Study 3
Research Question (RQs)	RQ1: What is the impact of Industry 4.0 and Circular Economy on Lean Culture and Leadership?	RQ2: How could leaders assess their competencies to embrace Industry 4.0 and Circular Economy?	RQ3: How do regional contexts influence Circular Economy capability development?
Method	Systematic Literature Review	SLR + Maturity Model Design	Comparative Qualitative Case Studies
Analytical Approach	Inductive theory building	Maturity model design	Gioia methodology
Primary Output	19 LL competencies, 10 LC characteristics; Industry 4.0 and Circular Economy impact analysis	DGL maturity model: 7 dimensions, 29 subdimensions, 81 capabilities, 5 levels	4 aggregate capability dimensions across European and Middle East contexts
Publication	ERMBE, 2024 10.1016/j.iemeen.2023.100232	TQM&BE, 2024 10.1080/14783363.2024.2347373	Prepared for submission.
Thesis Chapter	Chapter 4	Chapter 5	Chapter 6

Table 3.1. Overview of the three studies comprising the thesis research design. LL = Lean Leadership; LC = Lean Culture

3.2.2 Integration Across Studies

Three features ensure the studies function as an integrated investigation rather than independent exercises. All three studies share the same theoretical foundations established in Chapter 2 (the DGL concept, the distinction between culture and leadership, and the identification of I4.0 and CE as the concepts moderating Lean transformation). This shared grounding ensures that the findings from each study are interpretable against a common conceptual reference.

Equally important is the consistent unit of analysis across all three investigations: the organization, specifically operating units within large multinational corporations in process

manufacturing. This consistency enables meaningful cross-study comparison rather than merely sequential accumulation.

The sequential dependencies described above and made explicit in Chapters 4, 5, and 6, constitute the third binding feature of the design; they are synthesized and examined in Chapter 7. The cross-study integration presented in Chapter 7 also operates as a quality check, as described in Section 3.6.3: coherence across three methodologically independent studies strengthens confidence in each, whereas incoherence would indicate either methodological weaknesses or theoretical complexity requiring further investigation.

3.3 SYSTEMATIC LITERATURE REVIEW METHODOLOGY

Studies 1 and 2 both employ systematic literature review (SLR) as their primary method, addressing different questions through a common protocol. Study 1 uses SLR to identify how I4.0 and CE affect Lean Culture characteristics and Lean Leadership competencies. Study 2 uses SLR to assess existing maturity assessment frameworks and identify the structural gaps that a new DGL model must fill.

3.3.1 Rationale for Systematic Literature Review

Both RQs addressed by these studies require comprehensive synthesis of existing knowledge rather than primary data collection. RQ1 concerns the impact of established concepts (I4.0 and CE) on well-documented constructs (Lean Culture and Lean Leadership): answering it requires assembling and analyzing what existing research has established about those relationships. RQ2 requires understanding what assessment frameworks already exist and where gaps remain. Both questions therefore call for a method that is transparent, replicable, and capable of limiting researcher bias in the selection and interpretation of sources (Seuring et al., 2020; Tranfield et al., 2003).

Following the classification proposed by Seuring et al. (2020), both studies employ an inductive, theory-building approach to the literature review. The review begins with established foundations in Lean Culture and Lean Leadership literature and examines how the introduction of I4.0 and CE concepts modifies, extends, or challenges existing understanding. The literature review in Study 2 focuses specifically on maturity- assessment frameworks, synthesizing existing models to identify the structural gaps that inform the design of the new DGL maturity model.

3.3.2 Search Strategy

Both reviews followed the same five-stage articles selection protocol adapted from established SLR guidelines (Kovács & Spens, 2005; Seuring et al., 2020; Tranfield et al., 2003):

- Gross search: Keywords searched across Web of Science and Scopus, with no date restriction, to capture the full trajectory of relevant research.
- Refined search: Results filtered by language (English or Spanish).
- Preliminary analysis: Duplicates removed by title and DOI matching; additional articles from reference list reviews added where appropriate.
- Relevance screening: Titles and abstracts reviewed to remove articles unrelated to the specific RQ.
- In-depth analysis: Remaining articles read in full; only those containing information directly relevant to the RQ were retained, with extracted information recorded systematically.

3.3.3 Search Equations

The search equations are distinct from the five-stage selection protocol described above: they define the thematic scope of the search, while the protocol governs how articles identified through each equation are selected and retained.

Study 1 comprised four search stages, each targeting a specific aspect of the DGL concept. The stages progressed from foundational to integrative, allowing understanding **to develop cumulatively**.

Stage	Focus	Search Equation
1	LL & LC foundations	(Lean) AND (Leader* OR Cultur*) AND (Assessment OR Survey OR Questionnaire OR Evaluation)
2	LL & LC moderated by Industry 4.0	(Lean) AND (Leader* OR Cultur*) AND (Industr* 4.0 OR Fourth Industrial Revolution OR Digitalization OR Cyber Physical Systems OR Digital Transformation)
3	LL & LC moderated by Circular Economy	(Lean) AND (Leader* OR Cultur*) AND (Circular Economy OR Circular Manufacturing OR Green Operations OR Green Manufacturing OR Sustainable Manufacturing)
4	LL & LC moderated by Industry 4.0 AND Circular Economy	(Lean) AND (Leader* OR Cultur*) AND (Industr* 4.0 OR Fourth Industrial Revolution OR Digitalization OR Digital Transformation) AND (Circular Economy OR Circular Manufacturing OR Green Manufacturing OR Sustainable Manufacturing)

Table 3.2. Study 1 search equations across four stages. LL = Lean Leadership; LC = Lean Culture

Study 2 employed a single targeted search equation focused on maturity assessment frameworks at the intersection of the relevant concepts:

(Maturity OR Assessment) AND (Lean AND (Culture OR Leadership) AND (Industry 4.0 OR Circular Economy OR Digital OR Green))

3.3.4 Search Results and Selection

Study 1 generated 139 initial relevant papers across the four stages. After applying the five-stage protocol, 82 articles were retained for in-depth analysis. These 82 papers provided the evidence base for identifying 10 Lean Culture characteristics, 19 Lean Leadership competencies, and the mechanisms through which I4.0 and CE affect each. The full selection process is documented in Chapter 4.

Study 2 generated 46 documents from the initial search. After duplicate removal (23 eliminated), abstract screening (12 eliminated), and full-text analysis (5 eliminated), six articles were retained as directly relevant to maturity assessment framework design, five from the systematic search and one from narrative review. The small final corpus is analytically meaningful in itself: the absence of comprehensive frameworks integrating Lean Culture and

Lean Leadership with I4.0 and CE confirms the research gap that the DGL maturity model addresses. The selection process is documented in Chapter 5.

3.3.5 Analytical Approach

Both reviews extracted specific types of information relevant to the respective RQs. Study 1 systematically identified Lean Culture characteristics and their definitions, Lean Leadership competencies and their definitions, the specific impacts that I4.0 and CE have on each, and synergies and conflicts between concepts. Study 2 extracted the structural properties of existing maturity assessment frameworks (stages, dimensions, subdimensions, capabilities), the concepts each framework addresses, and the gaps that a comprehensive DGL model would need to fill.

The analytical approach was inductive in both cases: categories emerged from the evidence rather than being imposed a priori. It did not mean the reviews were theoretically empty. The conceptual foundations from Chapter 2, the distinction between Lean Culture and Lean Leadership, and the identification of I4.0 and CE as the key moderating concepts, provided a preliminary framework that oriented the extraction of evidence and its thematic organization. Inductive analysis within a theoretically oriented frame is consistent with the pragmatist epistemological stance described in Section 3.1, and it avoids two equally problematic alternatives: analysis that imposes prior categories regardless of what the data show, and analysis that treats every study as a standalone observation without interpretive context.

3.3.6 Limitations: Temporal Scope and Validation

Both reviews were conducted primarily during March–April 2021. Targeted validation searches conducted in 2024 during thesis finalization confirmed that no comprehensive frameworks addressing the identified gaps have been published in the interim period, thereby validating the continued relevance of the RQs.

The 2024 validation search employed the same protocol and databases (Web of Science and Scopus) used in the original reviews. For Study 1, the Stage 4 search equation, combining Lean Culture and Lean Leadership with both I4.0 and CE, was re-run with publication dates restricted to 2021-2024. For Study 2, the maturity assessment search was re-run for the same period. Although individual papers addressing pairwise combinations (Lean-I4.0 or Lean-CE) continued to appear, no frameworks integrating all three paradigms with explicit focus on

culture and leadership were identified. The most relevant papers published during 2021-2024 were reviewed in full and confirmed the persistence of the research gap, though they contributed to interpretation of findings in Chapters 6 and 7.

A targeted update search was conducted in April 2026 using the same protocol and databases (Web of Science and Scopus) employed in the original reviews, with publication dates restricted to 2024–2026. The search confirmed that the field has started to grow: several papers addressing pairwise combinations and 9 papers approaching tri-paradigm integration have appeared, where the most relevant are: Cannas et al. (2025); Elnadi et al. (2025); Hurta & Noskievičová (2025) and Vilaça et al. (2026), in a systematic literature review published in *Business Strategy and the Environment*, similarly conclude that systematic investigations into the combined Lean–Green–Sustainability–Industry 4.0 space remain limited. No framework integrating Lean, Industry 4.0, and Circular Economy with an explicit focus on culture and leadership maturity, empirically examined across contrasting institutional contexts, has been identified in the 2024–2026 literature. The two studies comprising Studies 1 and 2 of this thesis are being cited in papers approaching this field (Hurta & Noskievičová (2025); Bernhard et al. (2026); Shrivastava & Mishra (2025), indicating that the DGL concept is already being incorporated into the emerging literature rather than being superseded by it.

The restriction to English and Spanish may have excluded relevant research published in other languages. This limitation is common in business management doctoral research and does not materially affect the conclusions, given that the primary journals in these fields publish predominantly in English.

3.4 MATURITY ASSESSMENT DESIGN AND METHODOLOGY

Study 2 extends beyond literature review to include the design and construction of a maturity assessment model. The design methodology follows the phased approach proposed by Röglinger et al. (2012), comprising scope, design, populate, test, deploy, and maintain phases, adapted to the specific requirements of a DGL framework and informed by the structural classification proposed by Skalli et al. (2023). Five maturity levels were determined as sufficient to capture the full behavioral and organizational trajectory from reactive to fully integrated DGL capability, without introducing artificial differentiation between adjacent levels that would undermine practical usability.

The scoping phase defined four core properties that the assessment must address: (1) maturity levels or stages, reflecting sequential progression from reactive to integrated capability; (2) dimensions, representing the fundamental aspects of organizational DGL capability; (3) subdimensions, providing finer differentiation within each dimension; and (4) capabilities, specifying the concrete competencies and practices that characterize each level of maturity within each subdimension. The relationship among these four properties defines the model's architecture and determines whether it functions as a practical diagnostic instrument rather than merely a conceptual taxonomy.

The design phase translated SLR findings into model structure. The 10 Lean Culture characteristics and 19 Lean Leadership competencies from Study 1 provided the foundational content from which dimensions and subdimensions were derived. This translation required three interpretive decisions: First, related elements be grouped without losing analytical precision; Second, dimensions be sufficiently distinct to be assessed independently; and third, traditional Lean elements relevant to DGL be preserved while accommodating the genuinely new capabilities introduced by I4.0 and CE. Three principles guided these decisions: dimensions were defined to be conceptually distinct; subdimensions were created only where the literature review indicated meaningful differentiation in organizational capability development; and the developmental sequence with foundational Lean capabilities at lower levels and I4.0 and CE requirements emerging at higher levels, was preserved as a structural feature of the model rather than treated as an empirical assumption to be tested.

The resulting model comprises seven dimensions: leadership vision and strategic alignment; continuous improvement capability; digital technology integration; CE practices; stakeholder management; organizational learning; and performance measurement and feedback. These dimensions reflect the full organizational scope of DGL, extending beyond traditional Lean assessment dimensions to capture the cultural and leadership adaptations required by I4.0 and CE. Within each dimension, subdimensions capture the specific aspects most relevant to DGL; within digital technology integration, for instance, subdimensions address both the technical adoption of I4.0 tools and the leadership behaviors required to guide that adoption without undermining Lean disciplines.

The five maturity levels: Reactive (Level 1), Formal (Level 2), Deployed (Level 3), Autonomous (Level 4), and Way of Life / Culture (Level 5), reflect the organizational learning trajectory

described in the maturity model literature, moving from ad hoc responses through structured processes to continuous optimization. The progression from Reactive to Way of Life mirrors the original Lean transformation journey while incorporating the added complexity of three simultaneous cultural shifts. The 81 specific capabilities distributed across the model represent the granular content that enables organizations to assess their current position honestly and identify the specific development priorities that would move them forward. The full model specification is presented in Chapter 5.

The design process was iterative. As subdimensions were defined, their implications for maturity level descriptions were examined; as capabilities were specified, their coherence with the dimension and subdimension structure was verified. This iterative refinement ensured internal consistency across the model, with successive rounds of checking between structure and content reinforcing one another.

One clarification of philosophical consistency is required. The maturity model is a prescriptive instrument because it specifies developmental stages that organizations use to assess where they are and what to develop next. This does not conflict with the pragmatist stance adopted in Section 3.1. The five maturity levels are not claims about universal organizational laws; they are analytical constructs built from the systematic evidence of Study 1, designed to be useful in practice. Their validity is assessed by whether they enable accurate organizational diagnosis, not by whether they describe a fixed universal reality, which is consistent with design science research traditions (Hevner et al., 2004; Röglinger et al., 2012). The moderate realist ontology supports this: discernible patterns in organizational capability development can be structured into a developmental framework without overstating their universality.

3.5 QUALITATIVE RESEARCH DESIGN

Study 3 (Chapter 6) employs a comparative qualitative case study design to examine how regional institutional contexts shape organizational capability development for DGL. This section explains the case-selection logic, data collection procedures, analytical approach, and procedures to ensure rigor.

3.5.1 Scope and Rationale

While the DGL framework integrates all three paradigms, Study 3 narrows its empirical focus to CE capability development within Lean manufacturing contexts. This is a deliberate and

bounded methodological choice, not a limitation. The focus is directly aligned with RQ3, which asks how regional institutional contexts shape the development of DGL capabilities, specifically the I4.0-enabled CE capabilities, within established Lean systems, and is not intended as a general investigation of tri-paradigm integration. CE represents the newest and least understood element of DGL integration, particularly in process manufacturing organizations with established Lean foundations. I4.0 technologies feature in this study as the enabling infrastructure through which CE capabilities are operationalized where, for example, digital tracking of material flows, sensor-based monitoring, and AI-enabled waste optimization represent the connective layer between Lean operational discipline and circular resource management that the DGL framework theorizes. This role is analytically coherent with the DGL proposition itself: I4.0 does not constitute an independent transformation stream but the digital infrastructure that makes Lean-compatible CE transitions feasible. Study 3 tests this proposition empirically by examining how such I4.0-enabled CE capabilities develop under contrasting institutional conditions. Lean serves as the established operational baseline: both case companies have more than twenty years of Lean implementation experience, making it the foundation on which CE capabilities are being actively developed. Chapter 8 describes how this focused scope opens avenues for future research on full tri-paradigm integration.

Qualitative methodology is appropriate for Study 3 because RQ3 asks how capabilities develop within organizations, a process question requiring in-depth understanding of practices, decisions, and their contexts rather than measurement of static outcomes (Mohajan, 2018). The complexity of sustainability transitions within established manufacturing systems requires extensive contextual understanding that quantitative instruments cannot capture (Dierckx de Casterlé et al., 2021). The focus on how regional institutional environments shape development necessitates access to participants' interpretations of regulatory requirements, national vision initiatives, and stakeholder pressures, and to how such that sense-making translates into organizational action (Cypress, 2018). Semi-structured interviews are therefore used to obtain context-sensitive mechanisms that predetermined questionnaires are unlikely to surface (Hoffmann, 2007).

A comparative design enables systematic examination of whether the same types of capabilities emerge in different institutional contexts and whether the mechanisms through which they develop differ. The comparison is structural rather than statistical: it asks whether

both cases exhibit the same capability categories, and if so, whether the development pathways differ across institutional contexts (Yin, 2018).

3.5.2 Case Selection

Two multinational aluminum producers were selected through theoretical sampling, the approach that seeks maximum variation on the key theoretical dimension of interest while controlling for variables that would otherwise confound interpretation (Eisenhardt, 1989). Both companies meet the following selection criteria: global industry leaders with more than 7,000 employees; predominantly international customer base (80% or more of revenue from international markets); more than twenty years of Lean Manufacturing implementation experience; explicit CE commitments articulated in corporate sustainability strategies; and operations in both the European and Middle Eastern regions studied.

The contrast on institutional context is the study's primary analytical lever. The European operations from Germany, France, the Netherlands, and the Nordic countries, function within stringent environmental regulatory frameworks and established stakeholder accountability structures. The Middle Eastern operations, mainly from Gulf Cooperation Council countries, function within national leadership-driven circularity initiatives, particularly Vision 2030 and related programs, where CE is framed as competitive advantage and national strategic priority rather than regulatory compliance. This contrast allows examination of different forms of institutional pressure shape the same underlying organizational challenge.

The aluminum sector is a high-leverage empirical setting for this investigation. Aluminum is the second most widely used metal globally; production accounts for approximately 2% of global greenhouse gas emissions; and the material is 100% recyclable without quality loss, meaning the circular potential is high and the decarbonization pressure is intense simultaneously (International Aluminum Institute, 2023). This combination of significant environmental impact and genuine circular opportunity makes aluminum an appropriate context for examining capability development at the intersection of Lean operations and CE

3.5.3 Data Collection

Eleven semi-structured interviews were conducted across both companies, six in Europe and five in the Middle East, following established qualitative research protocols (Brinkmann, 2014; B. Saunders et al., 2018). All interviews took place between May 2021 and August 2022,

conducted either in person or via videoconference, and lasted between 65 and 120 minutes with an average of 83 minutes, generating a primary data corpus of approximately 910 minutes of recorded material. All interviews were video and audio recorded with participant consent.

Interviews began with open questions about circularity initiatives and stakeholder engagement before progressing toward specific capability development mechanisms. This sequencing allowed participants to articulate their own framings and priorities before the conversation shifted toward analytically relevant themes. Such an approach surfaces organizational realities that researcher-led questioning might otherwise miss. The interview guide was refined iteratively as early analysis identified themes requiring further exploration, consistent with theoretical sampling (Draucker et al., 2007).

Participants were selected to represent diverse organizational levels and functional roles directly relevant to DGL capability development:

Organizational Level	Europe (n)	Middle East (n)
Senior Executive	0	1
Sustainability Manager	1	1
Operations / Plant Manager	3	1
Lean Specialist	1	1
Supervisor	1	1
Total	6	5

Table 3.3. Distribution of interview participants by organizational level and region

The distribution ensures representation of both strategic-level perspectives such as regulatory pressures, investor expectations, corporate sustainability commitments, and operational-level perspectives including day-to-day implementation challenges, workforce engagement and process integration. Including Lean specialists and sustainability managers ensures that individuals with direct functional responsibility for the capabilities under investigation contribute substantively to the findings.

The interview guide is provided in Annex B.

3.5.4 Sample Adequation and Saturation

The sample of 11 interviews aligns with established standards for qualitative research employing Gioia methodology (Gioia et al., 2013; Magnani & Gioia, 2023) and with comparable studies in Lean manufacturing and CE research. Three criteria substantiate the adequacy of the sample.

Theoretical saturation was assessed during the analytical process. Core themes were established by interview 7, with subsequent interviews validating rather than generating new dimensions. Saturation was operationalized as the absence of new first-order codes across two consecutive interviews, tracked systematically in MaxQDA. With this, saturation was achieved by interview 9, with interviews 10 and 11 providing confirmatory evidence without introducing new conceptual content (Guest et al., 2006; Naeem et al., 2024).

The sample provides high information power as proposed by Malterud et al. (2016), due to the focused study aim, the direct relevance of participant experience to the RQs, the established theoretical framework guiding analysis, and the cross-case comparative structure that amplifies analytical depth beyond what any single case would provide.

Methodological precedent supports this sample size. Comparable qualitative studies employ similar numbers of interviews: Caldera et al. (2019) used 12 interviews for Lean SME research; Kurdve and Bellgran (2021) conducted 10 interviews for green Lean operationalization. Accordingly, the goal is analytical generalization and theoretical refinement rather than statistical representation of a population (Yin, 2018).

3.5.5 Data Triangulation

Interview data were triangulated through three additional sources. Corporate sustainability reports (2019-2024), internal presentations on CE initiatives, and environmental performance data from both companies provided contextual validation of interview accounts and enabled consistency checks between stated practices and documented corporate positions. Site visits to production facilities enabled direct observation of Lean practices and CE implementations in operational context, corroborating alignment between interview accounts and observable practice.

Member checking was conducted through structured follow-up sessions with five key informants in late 2024 (EU1, EU3, ME1, ME3, ME4), selected to ensure cross-regional

validation coverage. Each session lasted approximately 30 minutes and was conducted via videoconference. Participants were presented with the second-order themes and aggregate dimensions emerging from the Gioia analysis, together with the representative first-order quotes included in the data structure table. The purpose was to verify interpretative accuracy: whether the analytical constructs represented participants' organizational realities as they understood them. Participants confirmed the accuracy of the four aggregate dimensions and the representative quotes. They provided minor clarifications of terminology that were incorporated into the final write-up. No new first-order codes emerged from these sessions, and no substantive analytical changes were required, confirming thematic closure (Birt et al., 2016; Lincoln & Guba, 1985).

Although CE practices continued developing after the primary data collection period, the foundational Lean-CE integration mechanisms identified remained robustly relevant, as confirmed through continued corporate reporting and participant validation.

3.5.6 Gioia Methodology for Data Analysis

The analytical approach for Study 3 is Gioia methodology, developed by Gioia et al. (2013) and refined by Magnani and Gioia (2023). Gioia methodology is specifically designed for systematic theory development in organizational research. It provides a transparent, structured path from raw data to theoretical constructs. That traceability is not incidental. When interpretive judgment shapes every analytical stage, the credibility of conclusions rests on the researcher's ability to show how they were reached.

The methodology proceeds through three analytical stages. First-order analysis identifies themes using the language of informants themselves, the terms and framings that participants use to describe their experiences and practices. This preserves the sense-making for organizational members rather than translating their accounts into researcher categories. First-order concepts are coded directly from interview transcripts, maintaining close connection to the original accounts. Second-order analysis organizes first-order concepts into broader themes through constant comparison, drawing on emerging patterns in the data alongside relevant theoretical perspectives from the literature. Here is where the primary interpretive work occurs: understanding what the first-order concepts reveal about underlying organizational processes. The analysis moves iteratively between data and theory, neither imposing predetermined categories nor abandoning theoretical orientation.

Aggregate dimensions then integrate second-order themes into overarching constructs that capture the broadest patterns across the full dataset. These dimensions constitute the primary analytical output of the Gioia process and form the basis for the theoretical contribution of Study 3 (Chapter 6). Consistent with Gioia best practice, the resulting data structure is presented with illustrative first-order quotes, second-order themes, and aggregate dimensions to ensure transparency and auditability of the analytic trajectory.

Computer-assisted qualitative data analysis using MaxQDA 2024 facilitated the systematic coding process (Kuckartz, 2019), supporting data preparation, code system development, first-cycle and second-cycle coding, theme grouping, and comparative analysis across regional contexts. The analytical process generated 68 first-order codes across the 11 interviews, organized into second-order themes through iterative comparison, and ultimately consolidated into four aggregate dimensions. The complete data structure and sample quotations are presented in Chapter 6.

The coding approach combined deductive and inductive elements through abductive reasoning (Fereday & Muir-Cochrane, 2006). The theoretical framework from Chapter 2 provided initial orienting categories, but these were not imposed on the data. New themes were allowed to emerge gradually, and the relationship between emerging themes and existing theoretical categories was examined as the analysis progressed. This abductive stance is appropriate for examining how established constructs manifest under specific organizational and institutional conditions, enabling theory elaboration rather than mere confirmation.

3.5.7 Regional Comparison Logic

The comparative dimension of Study 3 is central to its contribution. The analysis does not assume that European and Middle Eastern contexts will produce fundamentally different organizational behaviors. It holds open the possibility that similar capabilities develop through different mechanisms, or that different institutional pressures converge on similar organizational responses, both of which constitute analytically meaningful findings.

The comparison operates at the level of capability development mechanisms rather than organizational outcomes. Both case companies have pursued CE implementation within Lean manufacturing systems and have achieved measurable results; the question is not whether they succeed but how the pathways through which they build capabilities differ. Focusing on

mechanisms rather than outcomes follows comparative case study logic (Yin, 2018) and aligns with the institutional perspective framing the study (Bruton et al., 2010). For each aggregate dimension, the analysis examines whether the second-order themes and first-order concepts differ systematically between regional contexts, and whether observed differences can be attributed to the institutional conditions identified in the case selection rationale: regulatory frameworks and stakeholder accountability structures in Europe versus leadership-driven national programs and strategic direction in the Middle East. Where similarities emerge across contexts, they indicate DGL capability-development elements that reasonably transcend specific institutional conditions and therefore carry the strongest claim to transferability.

3.6 QUALITY CRITERIA AND ETHICAL CONSIDERATIONS

3.6.1 Quality Criteria in Systematic Literature Reviews

The quality of systematic literature reviews rests primarily on the transparency and replicability of the process. Both Studies 1 and 2 ensure quality through documented search equations that enable other researchers to reproduce the searches; systematic application of the selection protocol, with decisions recorded at each stage; structured extraction procedures that reduce the scope for subjective interpretation in the coding of evidence; and independent review of both the processes and the analytical outputs by the thesis Supervisor and by an external SLR expert at key stages, complemented by full reporting of inclusion/exclusion decisions through a five-stage screening flow adapted from the PRISMA framework (Moher et al., 2009; Page et al., 2021).

3.6.2 Quality Criteria in the Qualitative Case Studies

Qualitative research employs trustworthiness criteria (Lincoln & Guba, 1985) rather than the validity and reliability measures used in quantitative approaches. Study 3 addresses the four primary trustworthiness criteria as follows: credibility, transferability, dependability and confirmability.

Credibility or the extent to which findings accurately reflect participants' experiences and meanings is supported by member checking with key informants, data triangulation across interviews, documents, and site observation, and Gioia methodology's emphasis on preserving informant language in first-order analysis, which reduces the risk of imposing

meanings that participants did not intend. In addition, coder cross-checks at key stages and the use of direct quotations in Chapter 6 further substantiate interpretive accuracy.

Transferability or the extent to which findings can inform understanding in other settings is addressed through thick description of the organizational and institutional contexts in which findings are situated. Readers can assess whether the contextual conditions described are sufficiently similar to their own settings. The comparative design explicitly supports this by identifying both universal and context-specific elements of capability development, thereby indicating what is most likely to transfer and what will require contextual adaptation.

Dependability addresses the consistency and reliability of the research process. It is ensured through the systematic nature of the Gioia methodology, a documented audit trail (memos, codebook versions, decision logs) maintained throughout the analysis, and the involvement of the thesis supervisor in reviewing coding decisions and theme development at key analytical stages.

Confirmability, the extent to which findings are grounded in the data rather than in researcher predisposition, is addressed through the transparent data structure presentation in Chapter 6, which traces the progression from first-order concepts drawn directly from informant accounts through second-order themes to aggregate dimensions. Traceability from codes to literal extracts is preserved in MaxQDA, enabling independent assessment of the evidentiary basis for each claim.

3.6.3 Cross-Study Quality Assurance

The multi-method design provides an additional quality mechanism through cross-study consistency checking. Study 3's empirical findings are interpreted against the frameworks developed in Studies 1 and 2. Where empirical observations from Study 3 align with the conceptual and operational categories from Studies 1 and 2, that alignment strengthens confidence in both the frameworks and the case findings. Where divergences appear, mainly around the institutional dimensions of DGL, they are treated as theoretically productive signals of scope conditions, as evidence that the empirical reality is more complex than the conceptual framework anticipated, rather than as data to be explained away.

Chapter 7 describes this cross-study integration in detail. The integration process functions as a quality check in a specific sense: if the three studies had produced fundamentally incoherent

findings across their methodologically independent vantage points, this would signal either methodological problems or genuine theoretical complexity requiring further investigation. The coherence achieved in Chapter 7, despite the divergences, provides evidence that the three studies examine the same organizational phenomenon from complementary angles. The temporal dimension of the studies reinforces this: Study 1's conceptual identification of competencies and capabilities at risk from I4.0 and CE adoption; Study 2's translation of those into assessable capabilities; and Study 3's empirical examination of which capabilities emerged as significant organizational challenges and achievements in practice. The extent to which the empirical findings validate, refine, or the boundaries specify the conceptual and operational frameworks constitutes a quality indicator.

3.6.4 Ethical Considerations

The research was conducted in accordance with standard ethical guidelines for doctoral research in the social sciences. The qualitative study involving human participants followed protocols consistent with business management research ethics standards, including informed consent, confidentiality protection, and voluntary participation. All procedures adhered to the ethics guidelines published by the University of Oviedo (2017).

All interview participants were informed of the purpose of the research, the nature of the data to be collected, and how findings would be used prior to agreeing to participate. Consent was obtained before each interview. Company identities and individual participant identities are not disclosed in the thesis: organizations are referred to by regional designation (European company, Middle Eastern company) and participants by alphanumeric codes (EU1, ME2, etc.) in the analysis and reporting of findings. Interview recordings and transcripts are stored on encrypted, password-protected drives with restricted access (primary researcher and thesis Supervisor only); raw data will be retained for a minimum of five years following thesis defense, and then securely deleted. The published papers constituting Chapters 4 and 5 were reviewed and approved by both co-authors prior to submission. The case study paper in Chapter 6 follows the same review process. Participants were informed that findings would be published in academic form, with identities protected as described.

NOTE: BIBLIOGRAPHY OF THIS CHAPTER

The consolidated bibliography for all references cited in Chapters 1, 2, 3, 7 and 8 is included in Annex A. Chapters 4, 5, and 6 are published or publication ready papers and therefore retain their original bibliographies as published or submitted.

CHAPTER 4: CONCEPTUAL DEVELOPMENT OF DIGITAL GREEN LEAN: SYSTEMATIC LITERATURE REVIEW

This chapter presents the first study of this thesis, addressing Research Question 1 through a systematic literature review that identifies how Industry 4.0 and Circular Economy impact Lean Culture characteristics and Lean Leadership competencies. The study develops the Digital Green Lean (DGL) conceptual framework by synthesizing existing literature and analyzing the key integration challenges across these three paradigms.

Chapter 4 is presented exactly as published, in its entirety. Tables and figures follow the same naming convention as when published, remaining independent from other chapters. Chapter 7 provides the cross-study integration and synthesis connecting this conceptual development with the maturity model operationalization (Chapter 5) and exploratory empirical corroboration through Study 3 (Chapter 6), as outlined in the overall thesis structure described in Chapter 1.

Published:

Gatell, I. S., & Avella, L. (2024). Impact of Industry 4.0 and circular economy on Lean Culture and leadership: Assessing digital green lean as a new concept. *European Research on Management and Business Economics*, 30(1), 100232. (<https://doi.org/10.1016/j.iedeen.2023.100232>)

Citations (as of April 14th, 2026): 52 (Web of Science), 66 (Scopus), 118 (Google Scholar)

IMPACT OF INDUSTRY 4.0 AND CIRCULAR ECONOMY ON LEAN CULTURE AND LEADERSHIP: ASSESSING DIGITAL GREEN LEAN AS A NEW CONCEPT

Structured abstract

Purpose: This paper aims to investigate the impact of Industry 4.0 (I4.0) and Circular Economy (CE) on Lean Leadership (LL) and Lean Culture (LC), providing insights into how Lean Manufacturing (LM) companies can adapt their leadership and culture styles to succeed in the new business environment.

Methodology: We have conducted a systematic literature review, focusing on the impact of I4.0 and CE on LL and LC.

Findings: The implementation of I4.0 and CE requires changes in Lean Leadership and culture styles to incorporate sustainability and digital transformation. This study identified ten Lean Culture characteristics –receptiveness, customer orientation, culture of respect, collectivism, performance orientation, power distance, authority distribution, working conditions, problem solving and continuous improvement– and nineteen Lean Leadership competences –personal stability, continuous improvement, zero-defects, personal behavior, process and lean expertise, customer focus, human centric, self-developing and learning, problem solving, empowerment, genchi genbutsu, teamworking, targets setting, targets deployment, self-transcendence, servant, experimental, customer & supplier development and flow– that are necessary for successful implementation of I4.0 and CE in LM companies.

Research implications: We introduce a new concept, Digital Green Lean (DGL), which combines the principles of I4.0, Circular Economy and culture and leadership principles of LM; it focuses on productivity and people, through sustainability and technology.

Practical implications: The integration of I4.0 and CE has a significant impact on LL and LC. LM companies must adapt their LL competences and LC characteristics to incorporate sustainability and digital transformation and to adopt a comprehensive approach that considers the needs of their business and engages employees in the process, creating a culture of continuous improvement.

Originality: Although there are some previous studies that analyze the relationship between lean management and I4.0 and/or Circular Economy, to the best of our knowledge, this study is among the first to investigate the impact of I4.0 and CE on Lean Leadership and Culture, contributing to the understanding of how companies can succeed in the new business environment.

Keywords: Lean manufacturing, Leadership, Culture, Industry 4.0, Circular economy.

1. INTRODUCTION

The so-called fourth revolution comes from the application and integration of new digital technologies into industry. The concept of Industry 4.0 (I4.0) arose through a German government initiative (Kagermann et al., 2013). For the first time, an industrial revolution was evaluated a priori and not ex-post (Sato Duarte et al., 2018). The smart factory is expected to be the result of this revolution, with key technologies that will help achieve productivity goals. These technologies will transform people's living and working conditions. The digital revolution could be a force for fair, sustainable development (Atasu et al., 2020).

Industry 4.0 comprises a broad range of technologies and tools, including: IoT devices and sensors; Cloud computing; Big data; Artificial intelligence and machine learning; Robotics and automation; Digital twins; and Cybersecurity.

The adoption of I4.0 is still in its initial stages, but it is expected to have a significant impact on the manufacturing industry in the years to come. According to a report by the World Economic Forum, the adoption of I4.0 could lead to a 4.5% increase in global GDP and a 15% increase in productivity by 2030 (World Economic Forum, 2019: <https://www.weforum.org/agenda/2019/11/the-fourth-industrial-revolution-is-redefining-the-economy-as-we-know-it/>).

Overall, I4.0 represents a major shift in the way that industries operate, with a focus on data-driven decision making, automation, and optimization. Aspects for Industry 4.0 implementation are: development of I4.0 specific know-how, securing financial resources, integrating employees into the implementation process, and establishing an open-minded and flexible corporate culture (Veile et al., 2019). While there are challenges and uncertainties associated with this shift, the potential benefits are significant, including increased efficiency,

productivity, and innovation (Ghobakhloo et al., 2021). As such, I4.0 is likely to continue to be a key area of focus for businesses and governments around the world in the years to come.

However, the adoption of I4.0 has challenges. One of the biggest is the need for workers with the skills and knowledge to use and keep innovative technologies. There is also the risk of job displacement as automation and robotics become more widespread.

To address these challenges, organizations are investing in training programs and other initiatives to help workers develop the required skills. Governments are also addressing the impact of automation on employment, with countries exploring the idea of a universal basic income to supply a safety net for workers who are displaced by automation (Au-Yong-Oliveira et al., 2019).

In sum, I4.0 is a significant shift in the way goods are produced and is expected to have a profound impact on the manufacturing industry in the years to come.

However, as we move towards a more technologically advanced society, it is important to consider the social and environmental implications of our actions.

Circular Economy (CE) is a relatively new concept that aims to optimize resource usage, reduce waste generation, and decouple economic growth from resource depletion (Kirchherr et al., 2017). The term "Circular Economy" was first coined by economists Pearce and Turner in 1990, and it has since been further developed and popularized by academics, policymakers, and industry practitioners (Geissdoerfer et al., 2017).

CE is built on the principles of "Reduce, Reuse, and Recycle." It aims to keep products, components, and materials at their highest utility and value always, and it involves designing out waste, pollution, and harmful practices from the start (Kirchherr et al., 2017). CE can be seen as a systemic approach that focuses on creating closed-loop material flows that are restorative and regenerative by design, rather than linear and wasteful (MacArthur, 2013).

The Circular Economy (CE) concept (MacArthur, 2013) is an example of how we can balance economic growth with sustainability, by reducing waste and maximizing the use of resources. Furthermore, the development of a super-smart society must prioritize the well-being of its citizens, ensuring that technology is used for the greater good.

CE has evolved from a niche concept to a mainstream movement, and it is gaining increasing attention from governments, businesses, and consumers worldwide. In 2015, the European

Commission adopted a comprehensive CE Action Plan, which includes ambitious targets (European Commission, 2015: https://environment.ec.europa.eu/strategy/circular-economy-action-plan_en). Similarly, China has launched its own CE Development Plan, which sets out a roadmap for resource conservation, eco-design, and green innovation (State Council of the People's Republic of China, updated 2021: https://english.www.gov.cn/statecouncil/ministries/202107/07/content_WS60e59652c6d0df57f98dc8be.html).

One of the technical features of CE is that it requires a system thinking approach. It involves collaboration and coordination between different stakeholders along the value chain, from design to disposal. It requires the adoption of innovative business models that prioritize product-service systems, leasing, sharing, and closed-loop supply chains (Geissdoerfer et al., 2017).

Despite the progress made, there are still challenges to overcome in the implementation of CE. One of the main challenges is the lack of market incentives and regulatory frameworks that support CE principles (Kirchherr et al., 2017). This includes issues related to intellectual property, taxation, and public procurement. There is also need for better metrics and indicators to measure the impact of CE initiatives and show their benefits (Geissdoerfer et al., 2017). Despite the challenges, CE is gaining momentum and offers a compelling vision for a more sustainable future.

Summing up, we can say that the current market and countries' economic situation has significantly changed the global economy, causing a shift in the business landscape, highlighting the need for digital transformation and sustainable business practices. I4.0 and CE are two emerging trends that are reshaping the business environment, and companies that adopt them are likely to remain competitive. The combination of I4.0 and CE can create a significant impact on production strategies by enabling a more efficient and sustainable manufacturing process. The integration of both models can lead to a circular production system that optimizes resource use, monitors the process and the efficiency, reduces waste, and ultimately creates a more sustainable production process (Moreira et al., 2010).

Besides, Lean Manufacturing (LM) –term coined by Krafcik (1988) and popularized by Womack et al. (1990) based on Toyota Production System (TPS)– has been a widely demonstrated production paradigm, proven to bring substantial improvements in efficiency, quality, delivery

and flexibility and customer satisfaction. With the rise of I4.0 and the need for more sustainable business practices, LM companies are also looking to incorporate CE principles and new technological advancements into their operations.

Lean Leadership and Culture must effectively implement and manage these changes. Leaders in LM organizations must have the competencies and skills necessary to navigate the complexities of implementing I4.0 and CE practices.

By examining the literature on LL competences and LC characteristics, as well as the impact of I4.0 and CE on them, this study aims to shed light on the necessary adaptations that must be made to support the transition to a more sustainable and technologically advanced manufacturing paradigm.

Considering the theoretical and practical background posed, to the best of our knowledge, this study is among the first to investigate the impact of I4.0 and CE on LL and LC, contributing to cover the research gaps identified, about the understanding of how companies can succeed in the new business environment.

Therefore, we propose the following research questions:

RQ1: “What is the impact of Industry 4.0 and Circular Economy on Lean Leadership and Lean Culture?”

RQ2: “How can organizations effectively integrate these concepts to drive operational excellence and sustainable growth?”

2. METHODOLOGY

This paper follows a systematic literature review (SLR) approach. According to Seuring (2020), SLR should limit bias in the assembly, critical appraisal, and synthesis of all relevant studies that address a specific question. The SLR was first used in 1995 in a medical document to find everything written about a specific topic for snowballing or pulling from references. Seuring (2020) categorizes SLRs into four types: theory building (inductive), theory modification (abductive), theory refinement (deductive internal), and theory extension (deductive external). This paper follows an inductive (theory building) approach, starting from a theoretical point of LC and LL, analyzing the impact of new concepts, and developing a new understanding. This method was developed by Kovács & Spens (2005).

The existing literature does not cover all the required aspects of the topics to the required level (Rusev & Salonitis, 2016). Therefore, this SLR will help to find knowledge gaps and gather appropriate information to cover the intersection between the four concepts mentioned above.

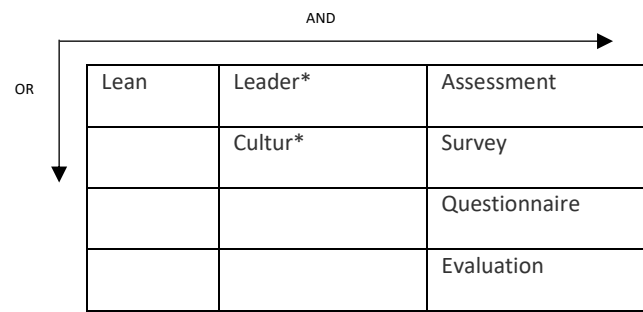
Papers Selection Criteria and Analysis Methodology is as described below:

1. Gross Search: Search keywords in Web of Science and Scopus databases.
2. Refined Search: Filter articles by language, (English or Spanish, mother language of the authors). No publication time restriction.
3. Net: Total documents found.
4. Preliminary Analysis: Remove duplications on title/DOI.
5. Topic Related: Analyze titles and abstracts to remove articles that are not related to the topic.
6. Relevance: Include relevant articles obtained from steps 4 and 5, as well as those found through narrative review.
7. Final Relevance: Read all remaining articles in-depth, capturing the required information for this paper. Remove articles that do not contain relevant information.

The last step of reading articles in-depth allows for a more comprehensive understanding of the information presented in each article and ensures that only the most relevant information is included in the SLR.

Our SLR comprises four stages to comprehensively understand the interconnections between Lean Culture, Lean Leadership, Industry 4.0, and Circular Economy.

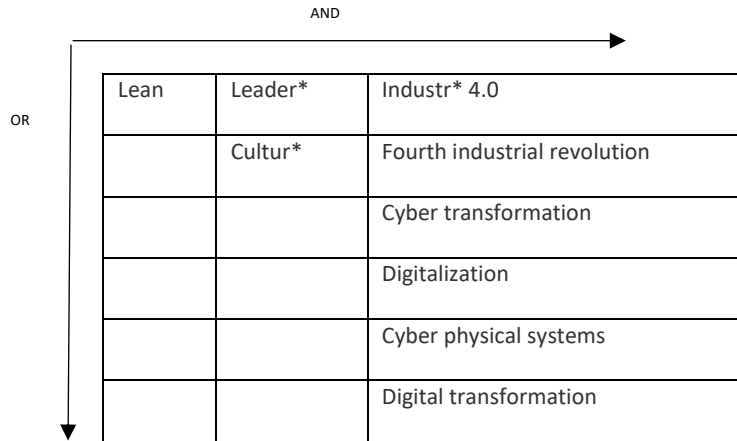
The first stage, performed on March 2nd, 2021, Table 1 aims to conduct an in-depth analysis of existing literature on Lean Leadership competences and Lean Culture characteristics.



Gross search:	Scopus 923 / WoS 861
Refined search:	Scopus 905 / WoS 777
Net:	1682 articles
Preliminary analysis:	1226 (456 duplications on title/DOI)
Topic related:	74 documents (1152 eliminated)
Total relevant:	TOTAL 81 relevant (including Narrative literature review: 7)
Final relevant:	55 (1 from 2004, rest after 2011)

Table 1: Stage 1- Search and selection criteria

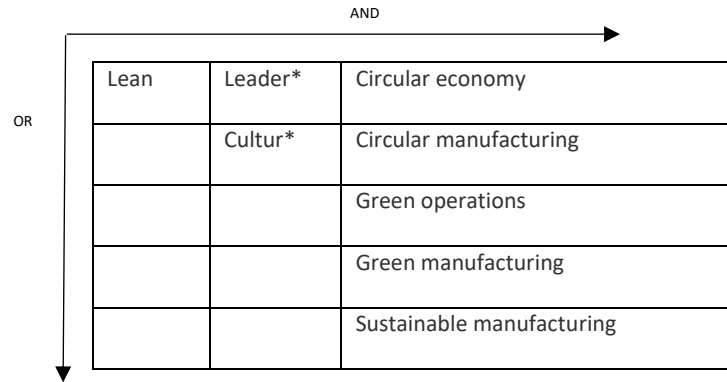
In the second stage, performed on March 25th, 2021, Table 2 shows the extent to which Industry 4.0 can improve Lean Culture and Leadership practices.



Gross search:	Scopus 52 / WoS 40
Refined search:	Scopus 51 / WoS 39
Net:	90 articles
Preliminary analysis:	67 (23 duplications on title/DOI)
Topic related:	30 Documents (37 eliminated)
Total relevant:	TOTAL 34 relevant. (Narrative literature review: 4)
Final relevant:	14 papers (all published after 2016)

Table 2: Stage 2- Search and selection criteria

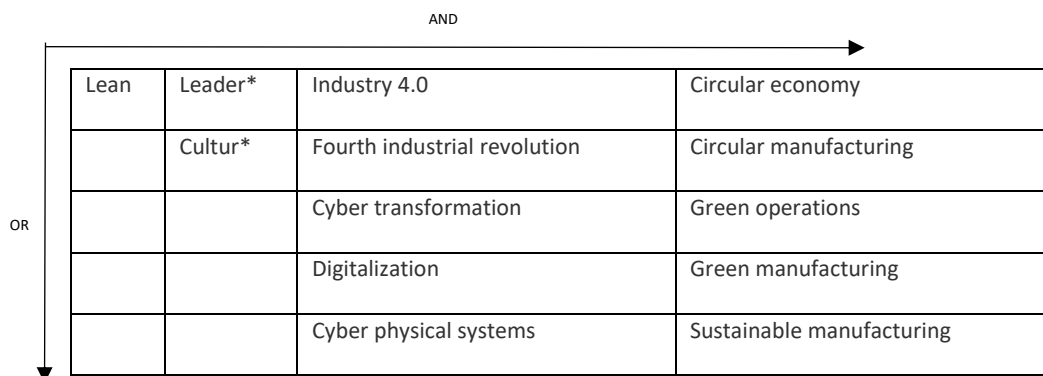
In the third stage, done on March 30th, 2021, and shown in Table 3, we will examine how the principles of Circular Economy can complement and enhance Lean Culture and Leadership practices.



Gross search:	Scopus 120 / WoS 84
Refined search:	Scopus 120 / WoS 83
Net:	203 articles
Preliminary analysis:	165 (38 duplications on title or DOI)
Topic related:	21 documents (144 eliminated)
Total relevant:	TOTAL 22 relevant (Narrative literature review: 1)
Final relevant:	11 papers (one published in 2005, rest after 2011)

Table 3 Stage 3- Search and selection criteria

and the fourth stage, done on April 4th, 2021, and shown in Table 4, will investigate how the adoption of Industry 4.0 and Circular Economy can impact Lean Leadership and Culture and explore any gaps in existing research.



Gross search:	Scopus 3 / WoS 5
Refined search:	Scopus 3 /WoS 5
Net:	8 articles
Preliminary analysis:	5 (3 duplications on title or DOI)
Topic related:	2 documents (3 eliminated)
Total relevant:	TOTAL of 2 relevant
Final relevant:	2 papers

Table 4: Stage 4-Search and selection criteria

By analyzing these impacts, we can gain a deeper understanding of the relationship between Industry 4.0, Circular Economy, and Lean practices. This knowledge can then be used to develop new insights and recommendations for organizations looking to implement Lean principles in the context of Industry 4.0 and Circular Economy and can then be used to guide further research and investigation.

3. RESULTS AND DISCUSSION

3.1. Lean Culture

Organizational culture (OC) refers to a shared pattern of values, behaviors, and basic assumptions that guide how a group perceives, thinks, and feels (Urban, 2015). OC is not directly observable but can be identified through symptoms and symbols in an organization, classified as clan, adhocracy, market, and hierarchy cultures (Salma et al., 2019; Tortorella et al., 2016). These cultures involve different leadership roles, as shown in Table 5.

ORGANIZATIONAL CULTURE	CHARACTERISTIC	ROLE OF THE LEADER
Clan / Group	Friendly work environment	Mentor / Father figure
Adhocracy / Development	Dynamic and creative	Innovator / Entrepreneur
Market / Rational	Get the job done	Hard driver / Competitor
Hierarchy	Structured work environment	Coordinator / Organizer

Table 5: Different organizational cultures (Source: Salma et al., 2019; Tortorella et al., 2016)

Lean Culture (LC) does not fit neatly into any of these culture classifications. Typically, companies practicing Lean Manufacturing tend to standardize processes, training, and leadership styles, fostering a unified culture.

LC was initially introduced by Liker (2004) through Toyota's 14 management principles, which are linked to OC. This research builds upon Liker's work and a previous SLR on LC conducted in 2018 by Dorval (2019). A total of 13 definitions of LC were identified, encompassing aspects such as organizational behavior, philosophy, thinking, ideologies, decisions, and leadership style (Péczeley & Liberona, 2017; Tortorella & Fogliatto, 2017). This indicates that LC is multidimensional.

Initial LC characteristics based on Hofstede and the Globe Study (House et al., 2004) are presented in Table 6.

Characteristic	Definition: the extent to which...
C1: Assertiveness	...organizations are assertive, confrontational, and aggressive in social relationships.
C2: Future orientation	...individuals in organizations engage in future-oriented behaviors such as planning, investing in the future, and delaying gratification.
C3: Human orientation	...individuals in organizations encourage and reward individuals for being fair, altruistic, friendly, generous, caring, and kind to others.
C4: In-group collectivism	... each individual express pride, loyalty, and cohesiveness in their organizations.
C5: Institutional collectivism	... organizational institutional practices encourage and reward collective distribution of resources and collective action.
C6: Performance orientation	... an organization encourages and rewards group members for performance improvement and excellence.
C7: Power distance	... members of an organization expect and agree that power should be unequally shared.
C8: Uncertainty avoidance	... members of an organization strive to avoid uncertainty by reliance on social norms, rituals, and bureaucratic practices to alleviate the unpredictability of future events.

Table 6: Preliminary LC characteristics

Most LC papers in literature align to varying degrees with these characteristics. Generally, lean organizations score higher than non-lean ones, except for assertiveness, which tends to be lower in lean organizations. In this paper, to align with LM literature, we will use "receptiveness" as the antonym for "assertiveness."

Wiengarten (2015) explored the impact of collectivism at the national and OC levels on the effectiveness of lean practices. It was found that national and OC collectivism positively influences lean practice implementation and effectiveness, except in cultures characterized by individualism. Studies like Netland (2016) empirically demonstrate the impact of Hofstede's dimensions on national culture, affecting areas like rewards, benchmarking, and external support.

Bortolotti (2015) examined the correlation between OC, soft lean practices, and the level of lean implementation. It was observed that companies with high lean performance exhibit higher collectivism, future orientation, human orientation, and receptiveness.

Furthermore, it is argued that an innovation culture should be an integral part of LC, as highlighted by Solaimani (2019) in the context of lean innovation management.

Situations characterized by unemotionality, depersonalization, subordination, conservatism, isolation, and antipathy can hinder transformation efforts, as discussed in Fadnavis' empirical study (2020). A summary of the final characteristics is presented in Table 7.

LEAN CULTURE CHARACTERISTIC	DEFINITION FOR LEAN ORGANIZATIONS
C1: Receptiveness	The degree to which organizations are low assertive, less confrontational, and soft in social relationships.
C2: Sustainable customer orientation	The degree to which organizations focus their systems on sustainability and long-term relationships with the customers and how the organizations engage in future-oriented policies such as planning, investing in the future, and delaying gratification to achieve it.
C3: Human orientation, culture of respect	The degree to which organizations are human-centric and how policies to reward individuals for being fair, altruistic, friendly, generous, caring, and kind to others are in place and used.
C4: Collectivism: In-group and institutional, level of unionization	In group: the degree to which each individual express pride, loyalty, and cohesiveness in their organizations and collaborates for a better company. Institutional: the degree to which organizational policies and practices encourage and reward teamwork and collective action through teams, committees, or any other form of unionism.
C5: Performance orientation	The way the organization sets the vision, mission and values and convert that into long term and short strategies and the extent to which an organization encourages and rewards group members for performance improvement and excellence.
C6: Power distance	The way the organization is built, the spans of control, the easiness of communication and the degree to which members of an organization expect and agree that power should be unequally shared.
C7: Authority distribution & decision making, Uncertainty avoidance	The distribution of authority at all levels of the organization, how failure is tolerated and what are the consequences in case of failure. The extent to which members of an organization strive to avoid uncertainty by reliance on social norms, rituals, and bureaucratic practices to alleviate the unpredictability of future events.
C8: Working conditions & EHS	The way the work is designed and standardized, the actual working conditions of the employees and the human centric EHS policies.
C9: Problem solving culture (scientific method)	The way the organization creates the need and strives for elimination of all non-value-added activities and the degree to which all employees participate are trained and coached by experience leaders in problem solving.
C10: Continuous improvement & innovation	The extent to which the mindset that everything can be improved is set in the organizational policies and deployed to all employees. To what extent are policies and systems used in the organization for innovation through employee participation at all levels.

Table 7: Final LC characteristics

3.2. Lean Leadership

Recently, mainly after 2010, companies have realized the importance of LL for successful lean implementation, however, have not modified their leadership systems so far (Dombrowski & Mielke, 2013). The behavior and competences of the Leaders are a fundamental area of research to understand, model, and quantify individuals in a Lean context (Donohue et al., 2019). Liker, in his 4P model (Liker, 2004) described a lean philosophy with a long-term thinking as a key part of the LL. Dombrowski & Mielke (2013) define LL as: “Methodical system for the sustainable implementation and continuous improvement of lean production system. Describes the cooperation of employees and leaders in their mutual striving for perfection. This includes the customer focus of all processes as well as the long-term development of employees and leaders”.

A common criticism is that there is no ready single model to develop and implement LL. Leadership at Toyota has been developed over the years and not based on a specific recipe. When implementing an LL model, companies usually wait to be told specific practical steps to implement them (Trenkner, 2016) and what are the best performance indicators to follow implementation. These two questions are not answered, and the bibliography is very scarce. However, Seidel et al. (2017) surveys 91 companies, showing that the companies understand and agree on the importance of LL, but they do not know how to apply it.

Lean leaders are the ones building and spreading the LC. Edgar Shein model, who links the OC with the LL and proposes three levels: 1) basic assumptions, 2) norms and values and 3) visible artifacts (Paro & Gerolamo, 2017). These categories are used as the first break up classification to easily organize the concepts, followed by a detailed classification for LL competences, where a “competence” can be defined as the set of abilities which enables the leader to use behavioral strategies to solve complex problems (Dombrowski et al., 2019).

Laureani and Antony (2018) discussed the combination of the lean leader with the nine leadership styles from Northouse’s book “Leadership: Theory and Practice” (Northouse, 1999), and arrived to the same conclusions: LL is not matching with any of the published leadership models completely, however it has higher similarities with transformational and servant leadership styles (Toledo et al., 2019) and includes other competences from the other models; therefore, a new full set of LL competences will be compiled.

Looking for a personality test to be done to lean leaders is not easy (Nielsen & Mathiasen, 2017). The studies show the low reliability of these tests because the personality traits are not well defined and the framework where they fit may change inside companies, sectors, and locations. Tortorella et al. (2016) argue that lean is an evolutionary process; therefore, there is more than one best way to lead teams implementing lean. This leadership style, called “situational leadership” ranges from directing to delegating, through coaching and supporting, depending on the relationship intensity between the leader and the employee. It is moderated by contextual factors such as age, experience of the leader, and size of the team. Situational leadership is found as the way the competences are used by the lean leaders, so the leaders will have to delegate, coach or support differently according to the status of the operations. “Situational leadership” will be included with all its components in the different LL competences.

Tortorella et al. (2018) argue, surveying Brazilian plants, that the traditional thinking of lean leaders is more relation-oriented than task-oriented. Maroukian (2020) reaches to the same conclusion when analyzing the Toyota Production System (TPS), where the author supports that Toyota is looking for modest leaders, not charismatic. Open to learn and teamwork-oriented leaders. Task-oriented leaders are positively associated with just in time and total productive maintenance production processes. This finding supports our intention to define a base line of LL and LC as a combination of earlier studies and experience.

To understand how LL competences are defined in the bibliography and the methods to measure it, Dombrowski (2014) depicts 15 lean leader competences for sustaining the implementation of lean over the time (See Table 8). Dombrowski (2013) proposes that the basic principles of LL are improvement culture, self-development, qualification, gemba and hoshin kanri and, he develops the leader competences for lean sustainable development.

L1: Leader stability in the position	L2: Promote CI through problem solving	L3: Zero-defects approach but tolerance to mistakes	L4: Hansei (self-reflection), self-awareness & assessment
L5: Deep process knowledge	L6: Customer approach	L7: Constantly developing and coaching his successor	L8: Constant self-developing and learning
L9: Master quick problem solving	L10: Shopfloor fact-based decisions	L11: Genchi genbutsu (shopfloor for data and coaching)	L12: Teamworking (span of control 1:5 to 1:10)
L13: Long term targets setting (not modified by short term ones)	L14: Consistent deployment and tracking employees with targets (Hoshin kanri)	L15: Striving for perfection	

Table 8: Preliminary LL competences

Seidel (2019) analyzes seven leadership theories and how can they help to define better LL competences, personal attributes, skills, and behaviors contributing to a better definition of the previous competences. In his literature for LL attributes, focused on the healthcare sector, Aij (2017), starting from Dombrowski (2013) analysis, adds few LL competences to the existing list, as emotional intelligence, visualizing greatness, trust, and fairness.

Van Dun et al. (2017) analyzes lean leaders' values and behaviors to evaluate them in a field case with effective lean middle managers. Starting from a SLR, refined using the Delphi method for consensus building, reaches 21 work values and 14 behaviors. All the values are already captured in our system. The behaviors are all included except for experimenting, structuring, and controlling that will be added to the final proposal. Another document from the same author (van Dun & Wilderom, 2016) elaborates further on the need of the Leaders to reach certain level of self-transcendent, being this the leader that breaks free from OC and focus on results, so they can work on a global scale realizing the impact of the company on other aspects of the life (social, environmental). Self-transcendence is added to the competences defined as "striving for perfection" and "visualizing greatness".

The role of high-level leadership in implementing LM was analyzed by Alefari (2017), from UK manufacturing companies. Comparing with the leader's competences, already included from the earlier papers, it is worth including the provision of adequate resources and the concept of time through the standardized work, takt time and cycle times.

When reviewing the cause-effect relations of lean soft practices to foster sustainable improvement, Costa et al. (2019) researched the critical success factors according to a SLR

conducted in 2019 and classifies them into three categories: cultural, organizational, and managerial. Out of the 24 factors identified, it is worth highlighting two of them: decentralized decision making and working conditions evaluation and level of unionized workforce. Same conclusion is reached when the relationship between lean leaders and healthy co-workers is analyzed (Bäckström & Ingelsson, 2015). They show that lean and healthy working conditions are moving in the same direction, however other studies show that the health conditions can be affected negatively by the application of LM (Parker & Slaughter, 1990; Rampasso et al., 2017).

Seidel (2017) conducts a SLR of lean competences, contrasting them with lean experts and confirming them with a survey of 91 companies from several sectors. It shows 16 LL competences. These competences are confirmed in terms of content and predictive validity. The survey shows that they are positively correlated with the level of lean implementation and maturity of the leaders with the lean systems. Seidel introduces the concepts of “operations flow” and “safety of the employee”, related to the human side (e.g., work stability, personal and professional). The same conclusion reaches Seidel with the concept of flow management and orientation.

Trenkner (2016) and Assen (2018) add the concept of servant leadership and transformational leaders in the LL equation. Servant refers to the humble leader with the role of serving the team, finding out ways to make employees work better, more successfully and to achieve better performance; transformational refers to the leader that detects the need, creates a vision, and guides the change. Nielsen (2017) proposes that the lean leader has a couple of traits that are important for this research: physical and psychological strength.

One of the concepts, described initially by Liker (2004), and empirically assessed in small and medium enterprises (Timans et al., 2012), is developing customers and suppliers as a key trait of the lean leader. This can be referred to both internal and external customers and suppliers, as also is described in the paper of Spear (2004) “Learning to Lead at Toyota”.

The leadership style differs for shopfloor leaders and for top leaders. Tortorella et al. (2017) analyze empirically the leadership for various levels of the organization, arguing that from the team leader to the general manager the preferred leadership style is moving from directing or coaching towards supporting. When reviewing the LL competences so far, they match with these leadership styles, therefore, we will not have the hierarchy as a moderator in this study.

The final lean leader competences proposed, after this SLR, are described in Table 9.

LEAN LEADERSHIP COMPETENCE	DEFINITION FOR LEAN MANUFACTURING ORGANIZATIONS
L1: Personal stability	Leader stability in the position for expertise and proper coaching.
L2: Continuous improvement and innovation	Enthusiastic and disciplined promotion of CI and Innovation through critical thinking, intellectual stimulation, and risk management.
L3: Zero-defects	Zero-defects mindset approach but tolerance to mistakes and failure when it happens as an opportunity for improvement.
L4: Personal behavior	Role model, hansei (self-reflection), self-awareness & assessment. Modesty & humility. Empathy. Credibility.
L5: Process and lean expertise	Deep "Process and lean" knowledge and application. Uses and implements flow, takt time and standardized work.
L6: Customer focus	Customer approach and focus on deliverables for internal and external customers. The need of the customer is above the need of the group.
L7: Human centric	Respect for people: Constantly developing and coaching his successor and the team. Emotional Intelligence, Ethics, and safety.
L8: Self-developing and learning	Constant self-developing and learning in a structure way, guided by an experienced teacher.
L9: Problem solving	Master quick problem solving and root cause analysis as a standard way of thinking. Capable of teaching and guiding others.
L10: Empowerment	Team empowerment and guidance & Fact-Based decisions after proper analysis.
L11: Genchi genbutsu	Constant presence on the shop floor as a philosophy for gathering data, understanding the situation, and coaching. Visual management as a key facilitator.
L12: Teamworking	Leads teams with span of control 1:5 to 1:10. Develop proper communication, transparency. Teams are above individuals. Social ability to make contacts.
L13: Targets setting	Communicate Vision: Long term targets setting (not modified by short term ones) and Values follower.
L14: Targets deployment	Consistent and transparent deployment and tracking of employees with challenging targets (Hoshin kanri) Reward and recognize success.
L15: Self-transcendence	Sets the true north. Always Striving for perfection and visualizing greatness (self-transcendence), Has physical and psychological strength and understands his contribution to the future of the organization and influence on employees personal and social life.
L16: Servant	Servant Leadership: Humble, trustful, listens to others, respectful and fairness.
L17: Experimental	Uses constant experimentation, hypothesis testing and trial (Kata): Standardizing the results, communicating the improvements, and recognizing the employees.
L18: Customer & supplier development	Developing customers and suppliers (internal and external) into LM for achieving higher levels of efficiency for the organization through process improvement and waste elimination.
L19: Flow	Understands the concept, importance and value of flow, stability, levelling, and balancing. Manage with Emphasis on flow rather than on isolated operations.

Table 9: Final LL competences

3.3 Lean Culture and Leadership and impact from I4.0

SLR Stage 2 is used to analyze and understand the impact that the application of I4.0 techniques could have on the LC and LL.

There is abundant bibliography on I4.0 since 2011 and there is an agreement that I4.0 may have a positive impact on the way shopfloors are managed and organized and influence organization's business models, products, and services (Tortorella et al., 2019). However, when understanding the impact of I4.0 on LC and LL, the literature is scarce. We try to understand the new or modified competences that the leaders in a lean organization need to adopt to effectively run areas where I4.0 is being implemented and the impact that I4.0 might have on the lean organization from a leadership and culture point of view. According to Pagliosa (2019) in total, 9 I4.0 technologies and 14 LM practices are identified and categorized according to different levels of both value stream application and synergy between them, none of them are related to LL/LC.

Lean and I4.0 diverge into a few concepts but converge in others. Authors discuss technical correlation matrixes but very few do the analysis on how lean leaders could manage production lines with I4.0 implemented. Scholars agree on both systems must live together: I4.0 must be built on LM and I4.0 improves the efficiency of LM (Bittencourt et al., 2019; Ciano et al., 2020; Rosin et al., 2020).

Companies are investing in I4.0 technologies now a days. The money gets locked into production machinery and therefore it needs to be depreciated and amortized, bringing a financial risk if not managed properly. By only developing digital versions of LM tools will not make a significant impact if not utilized as a part of a learning process for leaders and employees (Saabye et al., 2020).

Considering the origin and the intent of I4.0 is fair to say that the intention was not to change LL or CC but to progress on the digital revolution and digitalization. This progression brings changes into the behavior and style of leading the shop floor as well and it has a considerable influence on the way the teams are organized.

One of the principles of LM drafted by Toyota in their first document published in 1973 (Toyota Motor Co., 1973) is "automation with a human touch" (jidoka), intent to reduce the interaction between the man and machine so employee can increase time available problem

solving. We can assume that the technical tools on I4.0 can fall inside the automation technical part of lean (Sanders et al., 2016). We need to understand how those tools affect the competences of a lean leader and the aspects of the LC. The SLR is done to come up with the table below. The documents found are focused on the technical part of lean and I4.0 and the management and culture part of it is not included. Since there is not agreed yet commonality of terms and definitions, all the articles have been read and interpreted for aligning the terms as shown in the table below.

The main I4.0 tools have been defined according to the original paper from Kagermann (2013) on I4.0. The LL competences and LC aspects come from the earlier sections 3.1 and 3.2. All the elements combined are shown in Table 10.

DUSTRY 4.0 TOOL	IMPACT ON LEAN CULTURE CHARACTERISTICS	IMPACT ON LEAN LEADERSHIP COMPETENCES
Internet of things	Human orientation. Culture of respect (Saabye et al., 2020)	Zero-defects (Rosin et al., 2020) (Ciano et al., 2020) Problem solving (Rosin et al., 2020) (Saabye et al., 2020) (Dombrowski et al., 2019) (Tortorella et al., 2019) Flow (Ciano et al., 2020) (Sanders et al., 2016) (Tortorella et al., 2019) (Satoglu et al., 2018) CI & innovation (Sanders et al., 2016) (Tortorella et al., 2019) (Satoglu et al., 2018) Teamworking (Saabye et al., 2020) Customer & supplier development (Satoglu et al., 2018)
Augmented reality		Genchi genbutsu (Rosin et al., 2020) (Ciano et al., 2020) Teamworking (Rosin et al., 2020) Self-developing & learning (Rosin et al., 2020) (Ciano et al., 2020) Flow (Satoglu et al., 2018) (Zhao et al., 2019) Process & lean expertise (Satoglu et al., 2018) Human centric (Zhao et al., 2019)
Big data & analytics	Performance orientation (Saabye et al., 2020) (Rueb & Bahemia, 2020) Authority and decision making (Saabye et al., 2020) Working conditions & EHS (Saabye et al., 2020)	Problem solving (Rosin et al., 2020) (Saabye et al., 2020) CI & innovation (Rosin et al., 2020) (Dombrowski et al., 2019) (Satoglu et al., 2018) Process & lean expertise (Ciano et al., 2020) Empowerment (Ciano et al., 2020) (Saabye et al., 2020) Flow (Ciano et al., 2020) (Tortorella et al., 2019) (Satoglu et al., 2018) Customer focus (Sanders et al., 2016) Teamworking (Saabye et al., 2020) Experimental – Kata (Saabye et al., 2020) (Romero & Flores, 2019) Process and lean expertise (Dombrowski et al., 2019)

Autonomous robots	Human orientation, culture of respect (Romero & Flores, 2019) Working conditions & EHS (Rueb & Bahemia, 2020)	Flow (Rosin et al., 2020) (Ciano et al., 2020) (Satoglu et al., 2018) Zero defects (Rosin et al., 2020) (Ciano et al., 2020) Problem solving (Ciano et al., 2020) Servant (Ciano et al., 2020) Process and lean expertise (Dombrowski et al., 2019) CI & innovation (Satoglu et al., 2018)
Simulation		Problem solving (Rosin et al., 2020) Genchi genbutsu (Rosin et al., 2020) Flow (Rosin et al., 2020) (Ciano et al., 2020) CI & innovation (Rosin et al., 2020) (Ciano et al., 2020) Self-developing & learning (Rosin et al., 2020)
System integration	Sustainable customer orientation (Romero & Flores, 2019) (Rueb & Bahemia, 2020) Authority distribution & decision making (Rueb & Bahemia, 2020)	Flow (Rosin et al., 2020) (Ciano et al., 2020) (Tortorella et al., 2019) Customer/supplier development (Rosin et al., 2020) (Ciano et al., 2020) (Sanders et al., 2016) Teamworking (Sanders et al., 2016) Problem solving (Saabye et al., 2020)
Cloud computing		Teamworking (Sanders et al., 2016) Flow (Tortorella et al., 2019)
Digital twins	None	None
Cyber physical systems and security	CI and innovation (Romero & Flores, 2019) Performance orientation (Romero & Flores, 2019)	Problem solving ((Dombrowski et al., 2019) CI & innovation (Dombrowski et al., 2019) Teamworking (Dombrowski et al., 2019)
Additive manufacturing		Flow (Ciano et al., 2020) Zero-defects (Ciano et al., 2020) CI & innovation (Tortorella et al., 2019) (Satoglu et al., 2018)

Deep learning		Empowerment (Schmidt et al., 2020) Flow (Schmidt et al., 2020) Target setting (Schmidt et al., 2020) Target deployment (Schmidt et al., 2020) Genchi genbutsu (Schmidt et al., 2020) Experimental (Villalba-Diez et al., 2019) Problem solving (Villalba-Diez et al., 2019)
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Table 10: Impact of I4.0 on LC and LL

In the table there are no references of any impact of digital twins on LC and LL, also interesting to see that there is a very scarce bibliography on the impact of the I4.0 in the LC. Mainly highlights how the human orientation, performance orientation, working conditions, EHS and authority, and decision-making characteristics are affected by the introduction of new I4.0 technologies. This does not mean that the other LC characteristics cannot be affected by the introduction of I4.0 as there might be lack of studies on the subject. Most of the documents are published only from 2017 onwards, which shows a new field of investigation.

On the impact of I4.0 tools on the LL competences, only 12 out of 19 competences are impacted by I4.0. IoT and big data are the ones having more citations due to 1) the high impact of them on the LL competences or 2) the fact that those two I4.0 tools are the ones most known and studied. They are followed by augmented reality and robots, which also makes sense, considering that lean is defined as a human centric system and these tools pose the risk of making jobs redundant or changing the content. The LL competences most impacted by I4.0 are flow, continuous improvement, innovation, problem solving, teamworking, genchi genbutsu, and customer/supplier development.

3.4. Lean Culture and Leadership impacted by CE

Stage 3 is used to analyze and understand the impact that the application of CE principles could have on the LC and LL.

The three starting statements on CE are: (1) the world's resources are finite, (2) the consumption of resources of the human being is above the possibility of generation of the planet earth, and (3) the energy we are using for our development is scarce and based on fossil

fuel. Could we do, like humanity, something different to preserve the planet and, at the same time, continue with the evolution and development of society?

CE brings a full system redesign from linear economies “take-make-dispose” to “take-make-restore”, through 1) converting end-of-life concept to “restoration”, 2) use of renewable energy, elimination of hazardous chemicals and waste materials and 3) changing the consumer behavior from “owner” to “user” of the products. However, the elimination of non-added value activities is still critical as they consume energy, the minimization of any landfill material happens by design and the recyclability and refurbishment become part of the operations (Geissdoerfer et al., 2017; MacArthur, 2013).

CE has also some issues discussed such as (Geissdoerfer et al., 2017): 1) complexity of closed circle in growing demand, 2) social or employment problems as there will be less processing required due to longer use and elimination of the concept of obsolescence, 3) technical problems today as higher amount of energy required to recycle some materials compare with the new production, 4) customers preferring to own than lease will have an impact on the production lines and 5) the weak connection of sustainability with other economic aspects of the business.

Besides, CE, as a new management approach, could affect the lean leader competences and LC characteristics.

CE, at this stage, becomes more a modifier of the existing processes than a business model. It lacks some basic assumptions like productivity, employee social situation, economical balance, or transition from old production systems to new circular ones. Therefore, for this research, we would like to understand what impact CE is having on the competences of the LL and the characteristics of the organizational LC.

Table 11 shows the three operational principles of the CE that will have an impact on lean companies (MacArthur, 2013):

PRINCIPLE	DEFINITION
To increase material productivity: power the inner circle	Minimize the usage of resources for production by improving the process, bringing the reuse and recycle at all steps of the production line.
To Increase material productivity: power of circling longer	Maximize the number of cycles a product can be reused, remanufactured, or recycled.
To increase material productivity: power of cascade use	Diversifying the reuse across the value chain. Lines should be ready to take recycling material from other products or manufacturing lines that could fit into your lines, what requires a higher amount of flexibility but, at the same time, robust processes to ensure the quality is obtained at low cost.
To increase material productivity: power of pure circles	Increase of collection and redistribution efficiency by designing the use of uncontaminated material, while keeping quality.
To improve customer interaction and loyalty	Promote the leasing of products and return them to the manufacturer at the end of the usage cycle with performance contracts in place.
Less product complexity and more manageable life cycles	Promoting the manufacturing of basic “skeleton” products and considering everything else as an add-on. Shorter cycle times and higher customization while keeping portfolio specs relatively low.

Table 11: Operational principles of CE and its definition

While performing the SLR of these concepts, 22 documents were found, with some connection with this research, however only 11 documents were well connected to the topic (Table 12). They are connected only with environment or more broadly, with sustainability as LM is not green or sustainable per se (Chen et al., 2020; Lindskog et al., 2016).

Circular Economy principle	Lean Culture characteristic	Lean Leadership competence
Inner circles	Working conditions and EHS (Sorli et al., 2012) (Rothenberg, 2003) Performance orientation (Nadeem et al., 2019) (Ranky, 2010) CI & innovation (Rothenberg, 2003) (Ranky, 2010) Collectivism (Rothenberg, 2003)	Flow (Chen et al., 2020) (Sony & Naik, 2020) (Parmar & Desai, 2020) (Nadeem et al., 2019) Self-developing and learning (Chen et al., 2020) Target deployment (Chen et al., 2020) (Sony & Naik, 2020) (Rothenberg, 2003) Zero defects (Nadeem et al., 2019) (Ranky, 2010) Genchi genbutsu (Ranky, 2010)
Longer circles	Performance orientation (Nadeem et al., 2019) (Ranky, 2010)	Self-developing and learning (Chen et al., 2020) Flow (Sony & Naik, 2020) (Parmar & Desai, 2020) (Nadeem et al., 2019) Zero defects (Sony & Naik, 2020) (Nadeem et al., 2019) (Ranky, 2010)
Cascade use	Authority distribution and decision making (Sorli et al., 2012) CI & innovation (Rothenberg, 2003) Collectivism (Rothenberg, 2003)	CI & innovation (Sorli et al., 2012) (Rothenberg, 2003) (Ranky, 2010) Target setting (Chen et al., 2020) Empowerment (Chen et al., 2020) Teamworking (Chen et al., 2020) (Ranky, 2010) Flow (Sony & Naik, 2020) (Parmar & Desai, 2020) (Nadeem et al., 2019) Process & lean expertise (Parmar & Desai, 2020)
Pure circles		
Customer interaction & loyalty	Sustainable customer orientation (Sorli et al., 2012) (Parmar & Desai, 2020) (Nadeem et al., 2019) (Ranky, 2010)	Customer focus (Sorli et al., 2012) (Chen et al., 2020) (Sony & Naik, 2020) (Parmar & Desai, 2020) (Nadeem et al., 2019) (Ranky, 2010) Customer & supplier development (Parmar & Desai, 2020) (Ranky, 2010)
Product complexity & life cycles	CI & innovation (Nadeem et al., 2019)	

Table 12: Impact of CE on LC and LL

There is not much bibliography, and the existing one still has a big confusion of terms between green, sustainability and CE. In a brief analysis of the correlations, we can argue that the maximum impact happens on the topics related to manufacturing or customers.

In the LC characteristics, the ones most impacted are continuous improvement, innovation, performance orientation, and collectivism. In lean leaders' competences, the maximum impact is found on flow management, customer focus, and zero defects or striving for perfection, what is also logical as they are the most connected with the operations, where the biggest change happens in CE.

3.5. Lean Culture and Leadership impacted by I4.0 and CE

To analyze the overall combination of the concepts, Stage 4 is used.

It has been found that no articles cover I4.0 and CE having an impact on LL or LC. The articles found cover the technical part of the discussion, like tools and technical systems. They all argue that the companies using LM have a competitive advantage on the implementation of I4.0 (Varela et al., 2019) and, those having I4.0 tools and systems have a direct effect on the implementation of sustainability as triple bottom line approach.

The conjunction between the three concepts only triggers two papers. The first one, from Nascimento (2019) describes how I4.0 can be integrated with CE and, how quickly it can be integrated with existing production environments like LM. The second one from Salminen (2016) defends how LM and I4.0 develop superior competitive power through the main principles of CE. None of the two papers touch the leadership part of LM or the LC and how they can influence or be influenced by the application of I4.0 technologies or the CE principles.

4. CONCLUSIONS AND FUTURE RESEARCH

In today's fiercely competitive landscape, manufacturing companies face productivity challenges and rely on efficiency, cost reduction, customer focus, and low-cost innovation, often driven by employee-centered systems.

Lean Manufacturing (LM, based on Toyota Production System-TPS), initially perceived as a toolkit for waste reduction, has evolved into a culture rooted in values, principles, and behaviors that foster continuous improvement and waste elimination across organizations. Lean Leadership plays a pivotal role in cultivating this culture.

The development of Lean Leadership emphasizes coaching, empowerment, and respect for people and involves creating a culture of continuous improvement by supplying guidance and support to employees, encouraging experimentation, and learning, and promoting a shared sense of purpose and values. Lean Leadership is essential for the success of Lean Manufacturing, as it helps to create the conditions for continuous improvement and waste elimination.

Furthermore, due to the high cost of some techniques, the companies are moving resources and investments, initially dedicated to Industry 4.0, back to the operations line, trying to increase the circularity of their processes and reduce the impact on the planet earth. Industry 4.0 and Circular Economy have reshaped traditional Lean Manufacturing, emphasizing automated, circular processes for delivering customer value.

Our systematic literature review revealed that the integration of Industry 4.0 and Circular Economy affects Lean Leadership and Culture. It requires a comprehensive approach, tailored to an organization's unique needs, and a culture of continuous improvement. We anticipate the emergence of a novel concept: "Digital Green Lean" (DGL), fusing Industry 4.0, Lean Manufacturing, and sustainability principles.

4.1. Theoretical contribution

This review addresses a knowledge gap regarding how lean companies and leaders must adapt to Industry 4.0 and Circular Economy. We have identified ten key Lean Culture characteristics and nineteen Lean Leader competences that are most prevalent in the literature, providing an overarching view of Lean Leadership and Culture. However, a significant knowledge gap exists at the intersection of Lean, Industry 4.0, and Circular Economy, requiring further exploration.

Lean Leadership plays a pivotal role in implementing Industry 4.0 and Circular Economy while fostering a culture of continuous improvement. This leadership style prioritizes employee engagement, empowerment, and development, promoting collaboration and an environment where ideas are encouraged.

In conclusion, and answering the research questions mentioned above, the integration of Industry 4.0 and Circular Economy has a significant impact on Lean Leadership and Culture. To effectively integrate these concepts, organizations need to adopt a comprehensive approach that considers the unique needs of their business and engages employees in the process. This

involves developing a strategic plan that defines the organization's vision and goals and finds the key initiatives that will help to achieve these objectives. It also involves creating a culture of continuous improvement that encourages employees to share their ideas and opinions, and to take ownership of their work.

As of our knowledge cutoff in September 2021, there is no established framework to measure the impact of Industry 4.0 and Circular Economy on traditional lean companies, opening avenues for further research.

In summary, this review contributes to understanding the evolving concept of "Digital Green Lean" (DGL) and its potential in Lean Manufacturing. To the best of our knowledge this concept has never been used in bibliography before. We can define it as a combination of the principles of Industry 4.0 and Lean Manufacturing with a focus on sustainability. It involves the use of digital technologies to check and optimize production processes, reduce waste, and minimize the impact on the environment. Digital Green Lean builds upon the traditional understanding of Lean Manufacturing as a business culture and extends it to include the use of newly developed digital technologies.

4.2. Practical implications

Digital Green Lean (DGL) enables organizations to achieve operational excellence and sustainable growth simultaneously. By using digital technologies, organizations can collect real-time data on their production processes, identify inefficiencies and waste, and make data-driven decisions to optimize their operations. For example, sensors can be used to check energy consumption, water usage, and waste generation in real-time, allowing organizations to identify areas for improvement and reduce their environmental impact.

DGL also has a significant impact on Lean Leadership and Culture. Leaders who embrace DGL must be committed to sustainability and understand that it is no longer just a nice-to-have, but a necessity for long-term success. Specifically, Digital Green Lean Culture and Leadership interconnect the core of lean, culture and people, with the state-of-the-art digital technologies, and focuses on circularity and protecting the planet earth and its resources and inhabitants.

To effectively integrate DGL into their operations, organizations must first assess their current digital maturity and show areas where digital technologies can be used to optimize their

operations. They must also ensure that they have the necessary skills and ability to implement and manage these technologies effectively. Finally, they must communicate the importance of Digital Green Lean to their employees and ensure that they are engaged and motivated to embrace this novel approach.

To effectively implement DGL, organizations must adopt a culture of continuous improvement, embrace change and innovation, and ensure that their employees are engaged and motivated to embrace this novel approach. Consequently, we propose the specific term “Digital Green Lean Culture” as part of Digital Green Lean.

The findings of this literature review can help companies using Lean to understand the impact of Industry 4.0 and Circular Economy on their leadership and culture styles and adapt them accordingly.

4.3. Limitations and future research

Theoretical and practical contributions notwithstanding, our study is not free of limitations. This literature review is limited to a theoretical analysis of the impact of Industry 4.0 and Circular Economy on Leadership and Culture in lean manufacturers. Further investigation could be done to apply this concept of Digital Green Lean (DGL) and DGL Culture to a company so it can be measured, calibrated, measured, and improved. It will also help to evaluate the validity of the results, also comparing the impact to the effort needed to take the company to the next step.

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CHAPTER 5: OPERATIONALIZING DIGITAL GREEN LEAN: MATURITY MODEL DEVELOPMENT

This chapter presents the second study of this thesis, addressing Research Question 2 through the development of a comprehensive maturity model for assessing Digital Green Lean (DGL) culture and leadership implementation in manufacturing companies. Building on the conceptual framework established in Chapter 4, this study operationalizes the DGL concept by defining seven dimensions (three for culture and four for leadership), 29 subdimensions, and 81 specific capabilities assessed across five maturity levels (Reactive, Formal, Deployed, Autonomous, Way of Life / Culture). The 10 Lean Culture characteristics and 19 Lean Leadership competencies identified in Study 1 (Chapter 4) served as the foundational content from which the seven dimensions and 29 subdimensions of the maturity model were derived. Chapter 5 is presented exactly as published, in its entirety. Tables and figures follow the same naming convention as when published, remaining independent from other chapters. Chapter 7 provides the cross-study integration and synthesis connecting this maturity model operationalization with the DGL conceptual development (Chapter 4) and exploratory empirical corroboration through Study 3 (Chapter 6), as outlined in the Thesis structure described in Chapter 1.

Published:

Gatell, I. S., & Avella, L. (2024a). A maturity model for assessing Digital Green Lean Leadership and culture implementation in manufacturing companies. *Total Quality Management & Business Excellence*, 35(7–8), 860–897.

<https://doi.org/10.1080/14783363.2024.2347373>

Citations (as of April 14th, 2026): 12 (Web of Science), 14 (Scopus), 26 (Google Scholar)

Note: The annexes 1 & 2 referred in the text correspond to internal appendixes of this paper, not to the thesis level Annexes A and B.

A MATURITY MODEL FOR ASSESSING DIGITAL GREEN LEAN LEADERSHIP AND CULTURE IMPLEMENTATION IN MANUFACTURING COMPANIES.

Abstract – Lean Manufacturing is continuously transforming in the era of Industry 4.0, merging digital technologies with conventional manufacturing processes focusing on sustainability through Circular Economy principles. The newly developed term "Digital Green Lean."

The research is driven by the need for a maturity assessment for leadership and business culture, enabling companies using Lean Manufacturing principles to evaluate their readiness and alignment with the principles of Industry 4.0 and Circular Economy. Organizations must adapt their Lean practices to remain efficient, digital, sustainable, and competitive.

Method/Findings – The article consists of a literature review on maturity assessment, with the keywords Industry 4.0, Circular Economy, Lean Culture, Lean Leadership, and theoretical development for the maturity assessment, including evaluation criteria.

The framework includes (1) three dimensions, ten subdimensions, and 38 systems for Business Culture and (2) four dimensions, 19 subdimensions, and 43 skills for Leadership, assessed in a developed five maturity levels.

Implications – This research includes the first development of a maturity prescriptive and comparative assessment for companies to assess, compare, and develop action plans in their Lean journey within the context of Industry 4.0, Circular Economy, Lean Culture, and Lean Leadership, as part of the new integrated Digital Green Lean (DGL).

Keywords: Maturity model, assessment, Lean Manufacturing, Organizational Culture, Leadership, Industry 4.0, Digital Transformation, Circular Economy, Sustainability, Green production.

1.- INTRODUCTION

The Toyota Production System (TPS) has been widely studied since the 1980s following the publication of the book "Toyota Production System" (Toyota Motor Co., 1973) by Toyota, and it has regained interest in recent years. These studies cover the tools, but recently, the literature shows that implementing Lean Leadership and Culture systems is critical in achieving

and maintaining performance improvements for companies operating in Lean Manufacturing environments (Dorval et al., 2019; Liker, 2004; Spear, 2004).

The Fourth Industrial Revolution has emerged based on the industry's application and integration of new digital technologies. This concept of Industry 4.0, or the fourth industrial revolution, arose in Germany in 2011 through a government initiative published by Kagermann (2013) and represents a profound change in the organizational structure of companies. It is expected that the result of the Fourth Industrial Revolution will be the Smart Factory, or Smart Productivity, where Cyber-Physical Systems (CPS), the Internet of Things (IoT), Blockchain, and Big Data are the key technologies to achieve productivity goals.

Modern society is reducing the volume of material usage of economic systems to the carrying capacity of the planet's ecosystems through concepts like reusing, recycling, and remanufacturing. This means a radical decrease in economic systems' material and energy intensity (Melnyk et al., 2019), and this is where the Circular Economy kicks in. The concept evolved from a Smart Factory to a Smart Green Factory.

All the previous concepts are merged under one newly developed concept and lead to the definition of "Digital Green Lean" (DGL) (Gatell & Avella, 2024). It forms the foundation for exploring the current manufacturing landscape and gives companies a tool to evaluate their maturity in its implementation.

DGL helps us understand the impact of different aspects of current manufacturing on each other. By including sustainability, technological developments through Industry 4.0, Lean efficient practices, Lean Culture, and Lean Leadership, DGL is the basis for companies to evaluate and enhance their operational strategies. It enables organizations to adjust to the changing manufacturing environment while emphasizing environmental responsibility and resource efficiency.

With the concept of DGL in mind, we check the existence of a maturity model to assess the implementation grade and propose a new or improved maturity model that could add value to the organizations. A maturity model represents a desired, anticipated, or typical evolution path of a sequence of maturity levels for objects shaped as discrete stages (Becker et al., 2009). Becker (2009) also includes a classification for maturity models as descriptive, prescriptive, or comparative. If the model is explanatory, the entry will be a single point, and

the result will be without provision to improve maturity or assess the current condition. If prescriptive, it focuses on business performance over time and shows how to improve maturity, positively affecting the business. Moreover, if comparative, it will also provide benchmarking across industries or regions.

We can, at this point, include the research question that will be studied in this paper:

RQ: How can the design and development of a maturity model provide insights, recommendations, and foresight to organizations implementing Digital Green Lean to enhance the efficient management of its implementation, especially regarding organizational culture and leadership?

It is essential to investigate through a Systematic Literature Review (SLR) whether any maturity model in the literature or practice assesses the level of Industry 4.0 and Circular Economy implementation within the context of Lean Manufacturing. It should evaluate the traditional Lean practices and include topics related to Industry 4.0 and Circular Economy in the Leadership and Business Culture aspects. Besides, it should offer companies meaningful insights, recommendations, and foresight. If this model does not exist, a new model can be developed to effectively manage the implementation of DGL Leadership and Culture aspects.

2.- BACKGROUND

De Bruin *et al.* (2005) define the design of a maturity assessment framework in phases: scope, design, populate, test, deploy, and maintain. Also, Skalli *et al.* (2023) includes four core properties: (1) stages or levels, (2) dimensions, (3) sub-dimensions, and (4) capabilities/systems creating a suitable framework (evolution versus properties) to identify and create, if not available, a maturity assessment model.

The definition of the core properties of a maturity assessment to be used in this research will be as follows:

1. **Stages or levels of maturity:** Sequential stages of growth that an organization or a process goes through, reflecting its degree of advancement, proficiency, and efficiency.
2. **Dimensions:** Fundamental aspects or perspectives that contribute to the overall assessment of maturity

3. **Subdimensions:** Detailed elements or subcategories within each dimension. They represent the breakdown of broader dimensions into more specific components that can be assessed individually.
4. **Capabilities and systems:** Specific abilities, competencies, functionalities, or frameworks that contribute to the overall maturity of an organization or process (both tangible and intangible). Assessing capabilities or systems involves determining the presence, strength, and integration of critical elements driving maturity within each dimension and subdimension.

A Summary of these four properties and their interaction can be displayed in Figure 1.

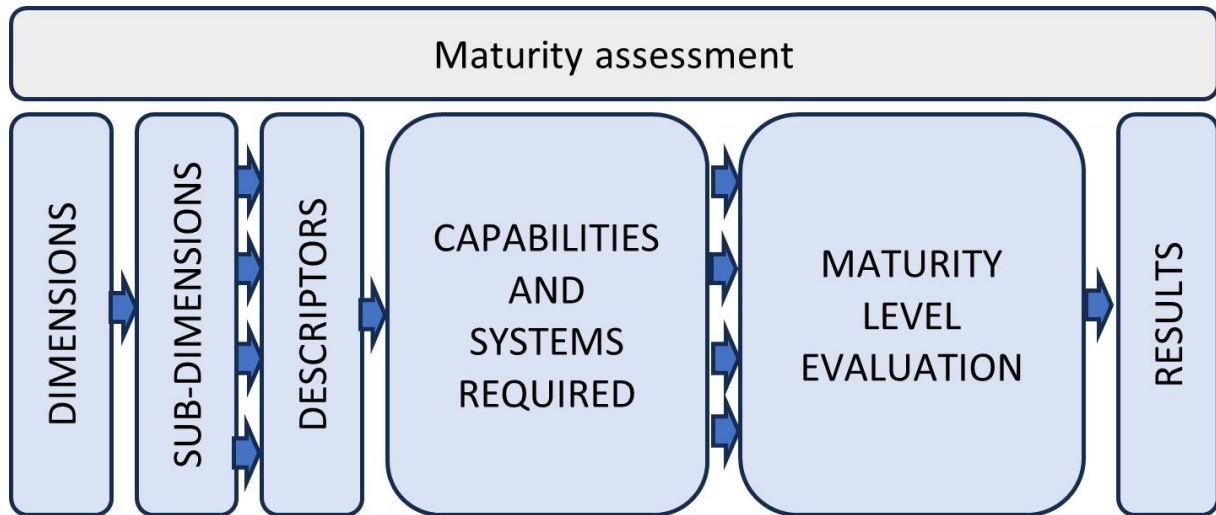


Figure 1: Visual representation of a maturity assessment

All the information and the existing bibliography on maturity models will help the authors in this paper define a proper methodology to respond to the research question. A Systematic Literature Review (SLR) should limit bias in the assembly, critical appraisal, and synthesis of all relevant studies that address a specific RQ (Seuring et al., 2020). Thus, this research paper starts with an SLR to understand the literature on maturity assessments in Lean Leadership, Lean Culture, Industry 4.0, Circular Economy, and their Boolean combinations (and/or).

To start working on the SLR, the paper selection criteria and analysis methodology are described below:

1. **Gross Search:** Search keywords in Web of Science and Scopus databases.
2. **NET / Refined Search:** Filter articles by language (English or Spanish, the mother language of the authors). There is no publication time restriction.
3. **Preliminary Analysis:** Remove duplications on title/DOI.
4. **Relevant:** Analyze titles and abstracts to remove articles unrelated to the topic. Include relevant articles obtained from the narrative review.
5. **Final Relevant:** Read all remaining articles in-depth, capturing this paper's required information and removing articles that do not contain relevant information.

A search question has been run on the Web of Science and Scopus databases to find any paper related to Lean Manufacturing Culture and Leadership, with Industry 4.0 and Circular, that will provide information on the availability of a maturity assessment and how to perform it.

2.1 SLR for the maturity assessment Lean & Culture, Leadership, Industry4.0, and Circular Economy

The outcome of this SLR should be a comprehensive assessment that includes the three concepts of Lean Manufacturing, culture and leadership, Industry 4.0, and Circular Economy blended into one unique maturity evaluation system.

Search Question (Table I): **(Maturity OR Assessment) AND (lean AND (culture OR leadership) AND (industry 4.0 OR circular-economy OR digital OR green))**

	Web of Science	Scopus
1 Gross search	28	18
2 Net (language filter)	27	18
3 Preliminary (merging and duplication elimination)	22	
4 Relevant (first analysis of abstracts and inclusion of narrative review relevant papers)	9+1NR	
5 Final relevant (Detailed reading of papers)	5	

Table I: Relevant articles for SLR

In this search, despite the final relevant articles, including the terms in the search, the maturity assessments need to be more comprehensive and cover the aspects of culture and leadership plus Industry 4.0 and Circular Economy, which we seek.

From an initial search of 46 documents, one was eliminated due to language, 23 were eliminated due to repetitions in the title or DOI, 12 were eliminated after reading the abstract and most relevant information, and five were eliminated after reading the entire paper. One was added to the narrative review. The total number of final relevant documents is five.

In the final five relevant articles, we can find, in whole or partially, the use of the same maturity assessment concepts described before (Skalli et al., 2023).

2.1.1.- Stages or levels of maturity

Out of the five final documents, only two define different stages of maturity, modified by the industry and sector they are researching, and focus either on Industry 4.0, Circular Economy, or Sustainability/Green. Tortorella and Fogliatto (2017) also define the Lean Implementation phases. However, none propose stages for combining Lean Leadership and Culture, Industry 4.0, and Circular Economy.

The maturity levels proposed in the two papers found in this part of the SLR are depicted in Table II. All of them range from a firefighting, reactive, or even infancy level of systems maturity at the beginning to a culturally embedded system, proficient or autonomous systems at the maximum maturity.

(Skalli <i>et al.</i> , 2023)	(Treviño-Elizondo <i>et al.</i> , 2023)
- Infancy: The company has planning for the implementation of Industry 4.0	- Value (process): Clear Vision of the value stream. - Sensitization (people): Current gaps in I4.0 to develop workers' skills. - Usable (Product): Customer wants and expects.
- Advanced: The company has developed vision 4.0 and workforce4.0	- Integration (process): connecting processes and standardizing cross-departmental information. - Adequacy (people): a training program to develop skills. - Traceable (product): Definitions of Customer use of the product.
- Skilled: The company started to deploy strategy 4.0 and pilot project	- Intelligence (process): automated decision-making processes and Business intelligence. - Adoption (people): Advanced technologies to support workers in data and decision-making. - Analyzable (product): The product provides data on usage.
- Proficient: The company has succeeded in its pilot project	- Collaboration (process): Between digitally interconnected processes and departments. - Promotion (people): High-performance teams. - Connected (product): The product connects, interacts, and shares information.
	- Autonomy (process): Flexible, adaptable, and innovative processes. - Culture (people): Best practices sharing and transferring. - Interactive (product): The product takes the initiative to look for interaction with smart devices.

Table II: Maturity Levels

2.1.2.- Dimensions/subdimensions

In the same way as the previous point, four of the five papers define different dimensions for a maturity assessment. However, they are only part of the research question we are investigating. Nevertheless, showing them four here is essential as they provide valuable information when defining and proposing a maturity assessment (Table III).

(Skalli <i>et al.</i> , 2023)	(Treviño-Elizondo <i>et al.</i> , 2023)	(Duarte, 2023)	(Gatell & Avella, 2024)
Technology	Smart Processes	Leadership and Strategy	Lean Culture: Values and Principles
Smart Value Chain	Smart People	People	Lean Culture: Customer Centric
Culture and People	Smart Products	Product	Lean Culture: Operational Excellence
External Environment		Process	Lean Leadership: Customer-Oriented
		Customer	Lean Leadership: Personal Development
		Supplier	Lean Leadership: Lean Principles
		Technology	Lean Leadership: Performance Driven
		Governance	

Table III: Dimensions in literature

We are looking for a maturity assessment focused on an organization's Leadership and Cultural aspects. Therefore, this table can be used as a starting point to define the dimensions in Section 3.2.

2.1.3.- Capabilities/systems

While defining the capabilities existing in the bibliography, we have found two articles that connect with our research, one with the title of “Lean-Green 4.0: A starting point for an assessment model” (Duarte, 2023), whose author gives an interesting approach to the capabilities or systems (“Measurement items” in his research), and another one that defines the competencies required for leaders managing Digital Transformation (Philip *et al.*, 2023). Both could be a starting point for developing the capabilities section from a maturity assessment (Table VII).

Duarte (2023) proposes a baseline framework to design an assessment model for implementing Lean and Green Management in an Industry 4.0 environment. Different dimensions were identified: “leadership and strategy, people, process, product, customer, supplier, governance, and technology.” Moreover, measurement items under each dimension show the author’s proposal on skills/capabilities for implementing such dimensions. The proposed framework is a starting point for designing an assessment model to guide the

deployment of Lean and Green Management characteristics within the new industrial era. However, it does not include a direct connection with the Company's Cultural aspects.

The maturity models in the literature cover either Industry 4.0 in the Lean industry, the most common, or the Sustainability or Green production in Lean companies. However, none of them are focused on Leadership and Culture as primary drivers for the Toyota Production System or Lean Manufacturing implementation as discussed by scholars (Liker, 2004).

In conclusion, for this SLR, any maturity models can evaluate the maturity of Leadership, Culture, Industry 4.0, and Circular Economy in those companies working under the umbrella of Lean Manufacturing. Despite some bits and pieces in the bibliography, to the best of our knowledge, a full maturity assessment has yet to be developed for Digital Green Lean Culture and Leadership as of December 2023, which allows us to certify a research gap to be covered.

3.-METHODOLOGY: CREATING A DGL CULTURE AND LEADERSHIP MATURITY MODEL

This section outlines the methodology for addressing the research question (RQ) and bridging the identified research gap. We include the steps to develop a robust maturity model that assesses the implementation of Industry 4.0 and Circular Economy within companies operating under Lean Manufacturing. The design and development of this model consider all studies examined during the Systematic Literature Review (SLR) process, ensuring the integration of perspectives and insights from the existing papers. This approach provides the robustness and relevance of the proposed model by incorporating best practices and insights identified during the systematic review.

This section defines dimensions, subdimensions, and descriptors for Lean Manufacturing culture and leadership, Industry 4.0, and Circular Economy. Later, we determine the capabilities or systems required for assessing maturity. All these pieces will give the maturity assessment model, shown in Section 3.4.

3.1.- Stages or levels of DGL leadership and culture maturity

We need to start with the different maturity levels to define the maturity model. Setianto & Haddud (2016) proposed a set of maturity levels when presenting a maturity model for Lean development practices in the manufacturing industry that are used as a starting point for this paper; however, enhanced and redefined for the concepts we are using here with the new

papers found through the SLR as outlined in Section 2. Table IV includes the final levels of maturity considered in this article and defined in depth by the authors for the new maturity assessment.

MATURITY LEVEL	DEFINITION
REACTIVE	Reactive and firefighting. No problem-solving in place. No planning or strategy. Isolated employees without autonomy: No planning of I4.0 or CE, their applicable tools, or implementation. Issues are dealt with when they happen with no formal structure.
FORMAL	Formal working structure with team learning. First, standards (policies, procedures, processes) are developed—essential Planning. Only area/topic specialists work with autonomy. There is an I4.0 plan, and the first circularities appear in the organization.
DEPLOYED	Systems and skills are deployed in dedicated teams and are goal-oriented towards Vision and Values. Process standardization. Planning, scheduling, and resourcing in place. Vision has been developed for I4.0 and CE implementation through employees.
AUTONOMOUS	Managed autonomously, most employees are involved at all levels—process learning. Processes interconnected. The organization deploys applicable I40 tools, implements internal and external circularities, and defines pilots where successful implementation can be measured.
WAY OF LIFE (CULTURE)	Continuous improvement. Daily habit with full empowerment of organization members. The I40 and CE are delivering positive results in the areas where they are applied. Smart people, processes, systems, and products are in place and sustainable.

Table IV: Final defined levels of maturity

3.2.- Dimensions, Subdimensions and Descriptors

After defining the levels of maturity to be used in our maturity assessment, we proceed to represent the different dimensions and subdimensions to be used and explain them through descriptors. The two searches before in the SLR are used to describe Business Culture and Leadership. The starting point is mainly the work done by Setianto and Haddud (2016), Duarte (2023), and Gatell and Avella (2024). The dimensions and subdimensions defined are displayed in Table V. We can present the “Characteristics” as the subdimensions in the Lean Culture and the “Competences” as the subdimensions in the Lean Leadership.

LEAN CULTURE DIMENSION	CHARACTERISTIC/SUBDIMENSION
LC1: Values and Principles	C1: Human orientation, culture of respect
	C2: Collectivism: In-group and institutional level of unionization
	C3: Power distance
	C4: Authority distribution & decision-making, Uncertainty avoidance
LC2: Customer-centric	C5: Sustainable customer orientation
	C6: Performance orientation
LC3: Operational excellence	C7: Receptiveness
	C8: Working conditions & SHE (Safety, Health & Environment)
	C9: Problem solving culture (scientific method)
	C10: Continuous improvement & innovation
LEAN LEADERSHIP DIMENSION	COMPETENCE/SUBDIMENSION
LL1: Customer-oriented	L1: Customer focus
	L2: Customer & supplier development
	L3: Teamworking
LL2: Personal development	L4: Personal stability
	L5: Personal behavior
	L6: Human-centric
	L7: Self-developing and learning
	L8: Empowerment
	L9: Self-transcendence
	L10: Servant
LL3: Lean principles	L11: Experimental
	L12: Continuous improvement and innovation
	L13: Zero-defects
	L14: Process and lean expertise
	L15: Problem-solving
	L16: Genchi genbutsu
LL4: Performance driven	L17: Target setting
	L18: Targets deployment
	L19: Flow

Table V: Dimensions and Subdimensions

Each of the subdimensions requires a description. The descriptor analyzes and describes the systems and processes needed for an organization to achieve DGL Culture or Leadership. Descriptors will help the organization take the high-level concept of Dimension and Subdimensions and turn them into actionable items, processes, systems, and behaviors expected to be implemented on the shop floor developed by the organizational leaders. Descriptors are generated based on the DGL methodology and the impacts of Industry 4.0 and

Circular Economy in Lean Leadership and Culture. It considers DGL a unique working system, not an addition of three different systems.

The descriptors for the defined dimensions and subdimensions of Culture and leadership are identified in Table VI below.

DIM	SUB	DESCRIPTOR
LC1	C1	- The company is developing and implementing policies for equal opportunities, fairness, and employee care. It engages the employees to become asset protectors. Systems are in place to support this. - Company is human-centric: Autonomous robots are introduced to support operations. Employees only supervise. Humans are prioritized versus technology for low-physical intensity jobs. The impact of interconnectivity and robotization would be fairness, equal opportunities, and employee care. - The whole organization is focused on sustainability and conserving natural resources.
	C2	- Employees express pride, loyalty, and cohesiveness and collaborate for a better company. Organizational policies and practices encourage and reward teamwork and collective action through teams, committees, or any other form of unionism. - The company promotes the association of employees in different internal and external groups and measures benefits. (e.g., Formal teamworking, health committees, working groups with customers or suppliers, unionism, social responsibility committees...) Teams are handled, and policies are drafted to control/support them. Employees become ambassadors of the company. National Culture impacts global or local policies, and it is measured. - Employees participate in operational decisions and SHE improvements. Consensus is reached for key operational innovations, including technology and process redesign for circularity. - The decentralized and agile decision-making process's impact is measured and improves teamwork. Technology and robotics are more variable. Circularity does not erode the team's cohesiveness and the leader's leadership style.
	C3	- Organization design, spans of control, ease of communication, and the degree to which members expect and agree that power should be unequally shared. - The systems to design organization structures and manning requirements, including robots, cobots, and other technology enhancements. Vertical and horizontal communication is embedded in the design of the organization. Employees accept the mandates by conviction and not by bureaucracy. The coaching policy is deployed and measured in the results.
	C4	- Personal authority distribution is done at all levels of the organization; there are control mechanisms to balance human/machine decisions, failure is tolerated, and consequences of failure are known. Employees strive to avoid uncertainty by relying on social norms, rituals, and standard practices to alleviate the unpredictability of future events. - There are controls to prevent biases, and the decisions are fact-based, removing tradition or intuition. - Job insecurity is dealt with to avoid uncertainty of the future due to the introduction of new technologies or circularities. - By using big data, analytics, and integration online of the physical systems, the variability of the

		processes is reduced. There is a strategy for data-handling and decision-making considering technology output. - Recyclability and reuse to reduce material usage impact the process variation. The uncertainty and the decision-making policies contemplate it. A straightforward problem-solving process is in place. A strategy exists to eliminate and minimize or control uncertainty in any system or process. - There is a balance between Lean, I40, and sustainability in product and process development.
LC2	C5	- The organization focuses the systems on sustainability and long-term customer relationships. - Customers engage in future-oriented policies such as planning, investing in the future, systems integration, and big data. - The organization builds long-term relationships with customers, including retention methods. - Organization handles the new type of customer: Moves from owning to leasing and impacts the circularity and productivity.
	C6	- The organization sets vision, mission, and values and converts them into long-term and short-term strategies for all aspects of the business, e.g., manufacturing, technology, and sustainability. It includes a strategy deployment system and measurement to track the implementation of the strategy. - Organization rewards group members for performance improvement. Employees are motivated to meet and exceed their personal and technical targets. There is a learning and development plan to train all employees in new skills coming from the strategy (e.g., new technologies, Industry 4.0, blockchain, data analytics, cyber-physical systems, circularity, sustainability, waste, and recycling strategies) - Circularity includes Customer products and by-products. The impact of the reuse and higher recyclability is measured and reported for continuous improvement. Policies and systems are in place to deal with waste in the long term, targeting zero waste. - Inner and extended circle projects enhance operational performance and productivity and are built-in as part of the process design. Cloud computing: Data is stored in the cloud and interconnectable. - Data is integrated along the value stream for decision-making and process performance. Internet of Things, Analytics, and real-time data improve production performance in a learning organization.
LC3	C7	- The company promotes social relationships with the community and other stakeholders. Digitalization of processes does not jeopardize the intent of clear communication. There is a process to deal with conflict. There are mechanisms to handle difficult situations and conflicts between employees, leaders, or areas. - There is no conflict between machines and humans; priority is given to human employees. Information, data, and analytics from technical systems are used in problem-solving and other innovation systems.
	C8	- There are SHE, working conditions, and ergonomic policies and systems. They are communicated and implemented across the employees; they participate in making their jobs safer and healthier. The best available technologies are used to separate man-machine to minimize risks. There is a system to deal with human error in SHE-related topics. - There is a strategy to place autonomous robots in high-risk areas and cobots requiring high physical effort. The technology eliminates, minimizes, or controls SHE risks. Results are measured through

		data analytics of big data. - There are systems in place to minimize the impact of the circularity (e.g., increase of recycling, internal and external, longer cycles, more use of scrap, reusing policies...). The employees are trained. - Redesign of operational processes, including inner circles and reviewing working conditions and SHE.
	C9	- The organization strives to eliminate non-value-added activities. Participating employees are trained and coached in problem-solving by leaders. Information technologies are used for data-based analysis and faster decision-making. - Production lines and cycles are constantly improved before digitalization to avoid automating the error. Simulations are made for every process or product redesign to optimize the improvement cycle and cost.
	C10	- The Organizational mindset of everything can be improved. It is set in the policies and deployed to all employees. Innovation policies and systems are used by employee participation at all levels. Employees are recognized and rewarded for their collaboration on innovation and continuous improvement. - Innovation and continuous improvement culture include digital activities, new technologies, cyber-physical and security systems, sustainability policies, and process redesign to include circularities. - The operational redesign process includes circularity as a critical building block, extending the use of recycling materials as part of new operational processes (Cascade use)
LL1	L1	- The company is focused on deliverables for internal and external customers. Customer needs are above individual or group needs. Customer targets are more important than individual targets. - External Customer processes are designed and integrated with Company data availability and analytics. - Leader competencies include customer focus, digitization, and sustainability to develop new digital circular processes for them. - Customer evolves into a data provider and becomes part of the production digital loop.
	L2	- DGL is developed for customers and suppliers. Systems integration is in place to achieve higher levels of efficiency through process communication (IoT) improvement and waste elimination. - Leaders are capable, knowledgeable, and have tools to develop DGL in their internal and external Customers and Suppliers. Leaders have clear role descriptions and authority.
	L3	- Leaders have straightforward organization and spans of control that guarantee employee coaching and development (ratio depends on the job complexity) - Leaders develop proper communication and transparency and have the social ability to make contacts. Robots are considered part of the team and an essential input for problem-solving and decision-making. - Leaders consider teams above individuals and design the organization structure with new technologies (e.g., IoT, AR, Big Data, Robots, system integration, cloud computing, cyber systems, sustainability, circularity, cascade use...)
LL2	L4	- There is a promotion policy, including horizontal promotions. Each position has minimum skills and stability to gain expertise and coaching. < UNK> A leader's evaluation system is based on soft skills, personal development, and hard skills. There is a skill-development matrix for leaders.

	L5	- Company culture is embedded in the daily work of the leader, creating role models. - Servant leadership style includes hansei (self-reflection), self-awareness, and assessment. Modesty & humility. Empathy. Credibility. Leaders promote professional relationships with the employees and are accessible. - The implementation of new technologies is done with collaboration and consensus with the team and puts the company's benefits above individual or team objectives. - Company leaders are experts in leading difficult conversations and managing conflict.
	L6	- The organization has a succession plan process attached to an individual development plan. - Leader constantly develops and coaches his successor and the team. - Leader handles the digitalization strategy and sustainability effort with emotional intelligence and ethics.
	L7	- Constant self-development and learning in a structured way, guided by a coach using available technologies (AR, digital twins...) - There is a specific leadership skills and competencies development plan. It includes social/personal/technical skills, new technologies (augmented reality, robotics, simulations...), sustainability, and inner/longer circularity principles.
	L8	- The company promotes team empowerment and fact-based decisions after data gathering and analysis. - Delegation of authority and accountability systems in place, measured and effective. Facts are separated from opinions for decision-making. - Data is shared across and not individual property. Autonomous robots, deep learning, and other systems provide data to the organization where/when it is needed or on demand.
	L9	- Leaders set the true north and strive for perfection by visualizing greatness (self-transcendence). Leaders have physical and psychological strength and understand their contribution to the organization's future and influence on employees' personal and social lives. - Leaders are allowed and willing to take challenges with implementing new technologies and are not afraid of consequences. - Their critical role in the organization is reinforced and empowered. (self-esteem, self-transcendence, and motivation).
	L10	- Leaders follow the servant model and are encouraged to be humble, trustful, listen to others, respectful, and fair. - Leaders use the development of new technologies and sustainability principles to teach and develop their teams. (AR, Digital Twins, robots...)
LL3	L11	- Leaders use data analysis, experimentation, hypothesis testing, and trial (Kata): Standardizing the results, communicating the improvements, and recognizing the employees. - New technologies enhance performance and increase productivity by designing experiments, simulations, big data, deep learning, artificial intelligence, or other suitable technologies. - Leaders balance technology implementation and sustainability to get the best for the organization.
	L12	- Organization promotes disciplined CI and Innovation through critical thinking, intellectual stimulation, and risk management. - System design includes new technologies (e.g., IoT, Big data and analytics, robots, simulations, cyber

		systems, and 3D manufacturing) and Circularity as critical elements. Results are more efficiency, less waste, higher productivity, and employees are more engaged.
	L13	• There is a zero-defect mindset and tolerance for mistakes and failure when they happen. • Human errors are dealt with based on intentionality and consequences through a progressive consequences policy. Learning is captured when mistakes happen. • There is a process to handle variability and error produced by the autonomous robots connected (IoT) and the consequences implemented.
	L14	• There is a process and knowledge to design, implement, and improve flow, takt time, and standardize work. • Leaders use augmented reality, big data, deep learning, artificial intelligence, robots, and other technology to support lean principles and improve process design, including circularities, sustainability, and productivity.
	L15	• Leader masters scientific problem-solving, data analysis, root cause analysis, and simulation as a way of thinking. Teaches and guides others. • Information technologies are used for data analysis and decision-making. Production lines, robots, and cycles are connected (IoT), integrated, and constantly improved. To optimize the improvement cycle and cost, deep learning and simulations occur for every process/product redesign.
	L16	• Leaders are constantly on the shop floor as a philosophy for data-gathering, understanding the situation, circularity status, and coaching. Visual management and digital data visualization are key facilitators. • Data gathering implementation is done where the data is needed, avoiding central data controls as much as possible. A daily management system requires augmented reality, simulations, and deep learning (AI).
LL4	L17	• There is a system to communicate its vision, mission, and values as long-term and short-term targets using digital information and quick data access. Targets for AI and autonomous robots are set separately and are part of the leader's responsibility. • Leaders recognize and reward achievements in real-time on the shop floor.
	L18	• Consistent and transparent target deployment and tracking (Hoshin Kanri). Reward and recognize success. • Autonomous robots, deep learning, AI, circularity, cascade use, and other new processes implemented are included in those targets. Responsibility for the outcome stays with the process owner.
	L19	• Leaders understand and use flow, system integration, stability, leveling, balancing, and inner and extended circles concepts. Manage flow rather than isolated operations with available tools like AR, Big data, cloud computing, simulation, deep learning, or digital twins. • Leaders improve processes from linear design to circular flow, where possible, using all the new technologies and tools and ensuring productivity and sustainability are maintained.

Table VI: Descriptors for each subdimension

3.3.- Capabilities/Systems

Once we have perfectly defined the dimensions and subdimensions through the descriptors, we must define what systems should run in the organization to ensure effective implementation of those dimensions and subdimensions for business culture and what skills the leaders must have to implement DGL effectively. This will provide the framework to evaluate the DGL maturity of the organization.

Systems for DGL Culture and Skills for DGL Leadership are developed based on existing tools, systems, and processes but tailored to a holistic system like DGL. The author's operational and academic experience has been used to create them. These tools, systems, and methods are now defined to include all the requirements so companies can benefit from this model, knowing the gaps of their systems versus DGL and being able to prepare a specific implementation plan for the gaps found.

The development of those systems should include everything needed for its management, such as the development of policies, processes, and procedures accordingly. Table VII captures all the systems and skills required in place.

DIM	SUB	SYSTEMS/SKILLS/CAPABILITIES REQUIRED
LC1	C1	• Equal opportunities, fairness, employee care • Asset Management • Autonomous Robots strategy • Sustainability
	C2	• Association of employees (internal and external) • National and local culture development • Employee participation in company management • Team-working and robotization • Lean Manufacturing, Agile, and Six Sigma • Leadership
	C3	• Organizational Design (Humans, Robots, Cobots) • Internal Communication • Decision Making Levels • Training, development, coaching and mentoring
	C4	• Levels of Authority and control (Power of authority) • Human errors and consequences • Data and facts-based decision making • Conditions of employment and code of conduct • Feasibility, Process capability, and Data analysis.
LC2	C5	• CRM: Customer Relationship Management • SLA (service level agreement) & Customer Satisfaction • Systems integration and big data. • Customer DGL development
	C6	• Vision, Mission, Values, and Purpose of the organization • Strategic analysis (long term, short term) and deployment • Objectives and targets setting • Product and process design and redesign • Data storage, handling, and analysis
LC3	C7	• External communication • Conflict management
	C8	• Safety, Health, and Environment • Behavioral Safety and human error • Autonomous and collaborative operational robots
	C9	• Value Stream Mapping • Scientific Problem Solving • Operational Simulations
	C10	• Continuous Improvement and Innovation • Reward and recognition

LL1	L1	• CRM: Customer Relationship Management • SLA (service level agreement) & Customer Satisfaction • Leader competence framework • Value Stream Mapping
	L2	• Job descriptions • Skills assessment & training needs analysis
	L3	• Organizational Design and Organizational Charts • Internal Communication • Digitalization strategy.
LL2	L4	• Promotions and Job Grades assignment process • Performance Evaluation
	L5	• Leadership competence framework • Negotiation Skills • Difficult conversations and conflict management.
	L6	• Succession planning • Individual development plan. • Development and Coaching • Emotional Intelligence
	L7	• Skills assessment & training needs analysis • Leader competence framework
	L8	• Team design and performance • Data-based decisions. • Delegation of Authority.
	L9	• Target setting and performance evaluation. • Leading by example. • Motivational tools.
	L10	• Leadership versus Management • Development and Coaching
	L11	• Process Management: Statistical control, In control and capable • Kata: Experimentation, testing, and trial. • Simulation techniques
LL3	L12	• Innovation system (Continuous improvement, process improvements, and system innovation) • Waste elimination and value stream mapping
	L13	• Error proofing (Poka-yoke) • Human error: Progressive consequences system
	L14	• Design, operate, and improve processes (DA of Toyota) • Industry 4.0 tools design and implementation: Digitalization strategy.
	L15	• Scientific problem solving

	L16	• Shopfloor management • Daily Management system • Observation skills
LL4	L17	• Strategy development (Hoshin Kanri) • Target setting • Rewards and Recognition program
	L18	• Strategy development (Hoshin Kanri) • Target setting
	L19	• Continuous flow (kanban, pull system line leveling, and balancing) • Process redesign (Toyota DNA)

Table VII: Systems, Skills, and capabilities required

3.4.- Maturity model proposed

Based on all the DGL Culture Characteristics defined and DGL Leadership competencies proposed, and considering the impact that I40 and CE could have on those two concepts, a maturity assessment, prescriptive and comparative, is presented. This will answer our RQ: **How can the design and development of a maturity model provide insights, recommendations, and foresight to organizations implementing Digital Green Lean to enhance the efficient management of its implementation, especially regarding organizational culture and leadership?**

The final design includes maturity levels from Section 3.1, dimensions, subdimensions, descriptors from Section 3.2, and capabilities/systems to be implemented for a successful DGL implementation from Section 3.3. The template to be used is included in Annex 1 for DGL Culture and Annex 2 for DGL Leadership and summarized in Figure 2.

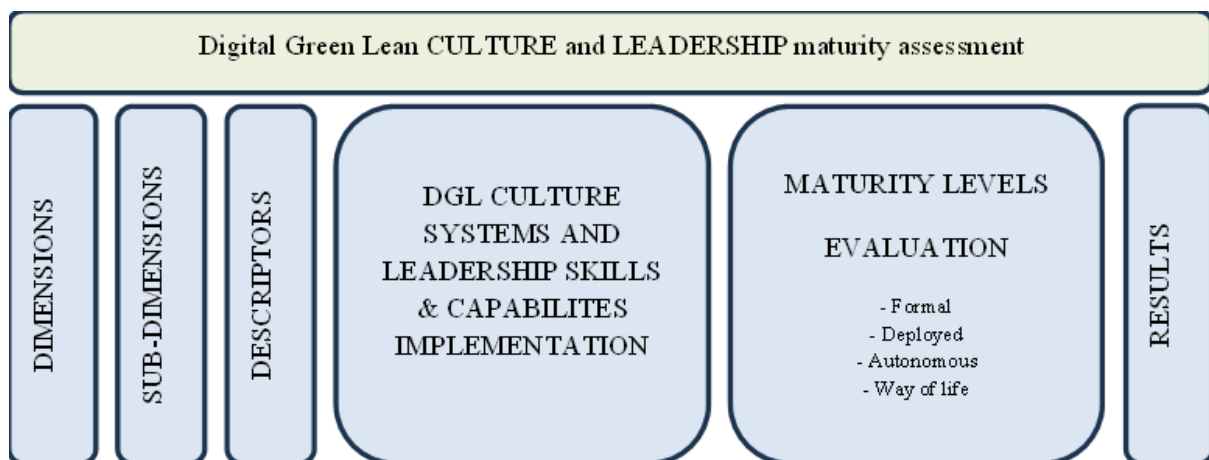


Figure 2: DGL Culture & Leadership Maturity Assessment

The organization should analyze the descriptors, systems, and skills required and reflect on how the company performs against the requirements. If any systems are in place and the organization is randomly using those processes, the cell of “reactive” should be checked. If some standards are in place, procedures, or processes drafted but not spread across the organization, “formal” is checked. When standard procedures are consistent in all the organizations, “deployed” is checked. When systems are working without intervention and are effective, the cell “autonomous” should be checked, and if the systems or skills are how we do things across the target area or organization, then the cell “way of life” is checked.

This system allows, but is out of the scope of this paper, to assign a value to each cell checked and develop a scoring system for the DGL implementation in an organization. This also helps the organization to perform the same maturity assessment over time, creating a longitudinal assessment to evaluate the implementation of Digital Lean Green, even becoming a performance metric for the company's top leaders.

4.- FINAL CONCLUSIONS, LIMITATIONS AND FUTURE RESEARCH

Lean Manufacturing has been undergoing continuous transformation since its inception. In modern times, new technologies and sustainability have become even more critical to achieving productivity and efficiency through the people in the organization. However, Lean manufacturing cannot work in isolation. Industry 4.0 and the Circular Economy are now indivisible building blocks of the overall business system, creating the concept of Digital Green Lean.

This merger of systems coined Digital Green Lean requires the company to gauge the integrated systems' various implementation levels and maturity. A complete business system design needs to be developed for DGL. However, to start with and to be aligned with the scholars, the first building blocks of the DGL implementation must be the company culture and leadership, proven to be the core of the Lean system in the literature. The rest of the tools or systems will be ad-hoc tailored to the organizational culture and leadership, following the same principles of efficiency and productivity.

Implementing Business Culture and Leadership skills must be measured, gauged, and improved. Therefore, we developed, not existing in literature as of December 2023, a maturity assessment that provides any organization with a tool to check both the level of advancement

in implementing the different systems or skills required for DGL and points out the gaps paving the way for new implementations impacting the company's bottom line while ensuring sustainable digital practices across the organization.

This maturity assessment contributes to the literature by providing a tool that contains (1) three dimensions, ten subdimensions, and 38 systems for Business Culture and (2) four dimensions, 19 subdimensions, and 43 skills for Leadership that give the organization's maturity and progress. It is the starting point for designing an assessment model to guide the deployment of all DGL characteristics within the new industrial era. It also contributes practically to the organization by possibly performing the maturity assessment and getting insights, recommendations, and foresight to effectively manage the implementation of DGL culture and leadership.

Duarte (2023) suggests a "starting point for the design of an assessment model." However, this paper proposes a full maturity assessment focused on the two main components of DGL: Company Culture and Leadership Skills.

This maturity assessment, prescriptive and comparative, will help manufacturing companies implement Industry 4.0 and Circular Economy, providing a systematic approach to evaluating the current cultural and leadership state, comparing it with other production centers, pinpointing areas for improvement, and strategically aligning the Lean initiatives with the evolving industrial landscape.

With this paper, the authors have tried to cover all areas of Culture and Leadership, using the existing literature and developing a novel maturity measuring system. However, some limitations to the research are required to be acknowledged. First, due to the final extension, this paper has not covered other operational dimensions and subdimensions, which are also very important for the business (e.g., value stream, process design, shopfloor design, financial aspects, scrap recycling, inventory management, remanufacturing, blockchain implementation, maintenance). Second, the tool's efficacy still needs to be tested within an organization, implementing all concepts to check its validity. Future research should include a partial or comprehensive assessment of a manufacturing organization, contributing to the empirical validation of the assessment tool.

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ANNEX 1: Maturity assessment form. DIGITAL GREEN LEAN CULTURE

DGL	DGL SUBDIMENSION		SYSTEMS REQUIRED	MATURITY ASSESSMENT				
DIMENSION	(Business culture)			REACTIVE	FORMAL	DEPLOYED	AUTONOMOUS	WAY OF LIFE
Values and Principles	Human orientation, culture of respect	•The company is developing and implementing policies for equal opportunities, fairness, and employee care. It engages the employees to become asset protectors. Systems are in place to support this.	• Equal opportunities, fairness, employee care					
		•Company is human-centric: Autonomous robots are introduced to support operations. Employees only supervise. Humans are prioritized versus technology for low-physical intensity jobs. The impact of interconnectivity and robotization would be fairness, equal opportunities, and employee care.	• Asset Management					
		•The whole organization is focused on sustainability and conserving natural resources.	• Autonomous Robots strategy					
			• Sustainability					
	Collectivism: In-group and institutional level of unionization	•Employees express pride, loyalty, and cohesiveness and collaborate for a better company. Organizational policies and practices encourage and reward teamwork and collective action through teams, committees, or any other form of unionism.	• Association of employees (internal and external)					
		•The company promotes the association of employees in different internal and external groups and measures benefits. (e.g., Formal teamworking, health committees, working groups with customers or suppliers, unionism, social responsibility committees...) Teams are handled, and policies are drafted to control/support them. Employees become ambassadors of the company. National Culture impacts global or local policies, and it is measured.	• National and local culture development					
		•Employee participates in operational decisions and SHE improvements. Consensus is reached for key operational innovations, including technology and process redesign for circularity.	• Employee participation in company management					
		•The decentralized and agile decision-making process's impact is measured and improves teamwork. Technology and robotics are more variable. Circularity does not erode the team's cohesiveness and the leader's leadership style.	• Team-working and robotization					
	Power distance		• Lean Manufacturing, Agile and Six Sigma					
	Authority distribution & decision-making, Uncertainty avoidance	•Organization design, spans of control, easiness of communication, and the degree to which members expect and agree that power should be unequally shared.	• Organizational Design (Human, Robots, Cobots)					
		•The systems to design organization structures and manning requirements, including robots, cobots, and other technology enhancements. Vertical and horizontal communication is embedded in the design of the organization. Employees accept the mandates by conviction and not by bureaucracy. The coaching policy is deployed and measured in the results.	• Internal Communication					
			• Decision Making Levels					
			• Training, development, coaching and mentoring					
Customer Centric	Sustainable Customer Orientation	•Personal authority distribution is done at all levels of the organization; there are control mechanisms to balance human/machine decisions, failure is tolerated, and consequences of failure are known. Employees strive to avoid uncertainty by relying on social norms, rituals, and standard practices to alleviate the unpredictability of future events.	• Levels of Authority and control (Power of authority)					
		•There are controls to prevent biases, and the decisions are fact-based, removing tradition or intuition.	• Human errors and consequences					
		•Job insecurity is dealt with to avoid uncertainty of the future due to the introduction of new technologies or circularities.	• Data and facts-based decision making					
		•By using big data, analytics, and integration online of the physical systems, the variability of the processes is reduced. There is a strategy for data-handling and decision-making considering technology output.	• Conditions of employment and code of conduct					
	Performance orientation	•Recyclability and reuse to reduce material usage impact the process variation. The uncertainty and the decision-making policies contemplate it. A straightforward problem-solving process is in place. A strategy exists to eliminate and minimize or control uncertainty in any system or process.	• Feasibility, Process capability and Data analysis.					
		•There is a balance between Lean, I40, and sustainability in product and process development.						
Operational Excellence	Receptiveness	•The organization focuses the systems on sustainability and long-term customer relationships.	• CRM: Customer Relationship Management					
		•Customers engage in future-oriented policies such as planning, investing in the future, systems integration, and big data.	• SLA (service level agreement) & Customer Satisfaction					
		•The organization builds long-term relationships with customers, including retention methods.	• Systems integration and bid data.					
		•Organization handles the new type of customer: Moves from owning to leasing and impacts the circularity and productivity.	• Customer DGL development					
	Working conditions & SHE	•The organization sets vision, mission, and values and converts them into long-term and short-term strategies for all aspects of the business, e.g., manufacturing, technology, and sustainability. It includes a strategy deployment system and measurement to track the implementation of the strategy.	• Vision, Mission, Values, and Purpose of the organization					
		•Organization rewards group members for performance improvement. Employees are motivated to meet and exceed their personal and technical targets. There is a learning and development plan to train all employees in new skills coming from the strategy (e.g., new technologies, Industry 4.0, blockchain, data analytics, cyber-physical systems, circularity, sustainability, waste, and recycling strategies)	• Strategic analysis (long term, short term) and deployment					
		•Circularity includes Customer products and by-products. The impact of the reuse and higher recyclability is measured and reported for continuous improvement. Policies and systems are in place to deal with waste in the long term, targeting zero waste.	• Objectives and targets setting					
		•Inner and extended circle projects enhance operational performance and productivity and are built-in as part of the process design. Cloud computing: Data is stored in the cloud and interconnectable.	• Product and process design and redesign					
	Problem solving culture (scientific method)	•Data is integrated along the value stream for decision-making and process performance. Internet of Things, Analytics, and real-time data improve production performance in a learning organization.	• Data storage, handling, and analysis					
	Continuous improvement & innovation	•The company promotes social relationships with the community and other stakeholders. Digitalization of processes does not jeopardize the intent of clear communication. There is a process to deal with conflict. There are mechanisms to handle difficult situations and conflicts between employees, leaders, or areas.	• External communication					
		•There is no conflict between machines and humans; priority is given to human employees. Information, data, and analytics from technical systems are used in problem-solving and other innovation systems.	• Conflict management					
		•There are SHE, working conditions, and ergonomic policies and systems. They are communicated and implemented across the employees; they participate in making their jobs safer and healthier. The best available technologies are used to separate man-machine to minimize risks. There is a system to deal with human error in SHE-related topics.	• Safety, Health and Environment					
		•There is a strategy to place autonomous robots in high-risk areas and cobots requiring high physical effort. The technology eliminates, minimizes, or controls SHE risks. Results are measured through data analytics of big data.	• Behavioral Safety and human error					
		•There are systems in place to minimize the impact of the circularity (e.g., increase of recycling, internal and external, longer cycles, more use of scrap, reusing policies...). The employees are trained.	• Autonomous and collaborative operational robots					
		•Redesign of operational processes, including inner circles and reviewing working conditions and SHE.						
		•The organization strives to eliminate non-value-added activities. Participating employees are trained and coached in problem-solving by leaders. Information technologies are used for data-based analysis and faster decision-making.	• Value Stream Mapping					
		•Production lines and cycles are constantly improved before digitalization to avoid automating the error. Simulations are done for every process or product redesign to optimize the improvement cycle and cost	• Scientific Problem Solving					
			• Operational Simulations					
		•The Organizational mindset of everything can be improved. It is set in the policies and deployed to all employees. Innovation policies and systems are used by employee participation at all levels. Employees are recognized and rewarded for their collaboration on innovation and continuous improvement.	• Continuous Improvement and Innovation					
		•Innovation and continuous improvement culture include applying digital activities, new technologies, cyber-physical and security systems, sustainability policies, and process redesign to include circularities.						
		•The operational redesign process includes circularity as a critical building block, extending the use of recycling materials as part of new operational processes (Cascade use)	• Reward and recognition					

ANNEX 2: Maturity assessment form. DIGITAL GREEN LEAN LEADERSHIP

DGL SUBDIMENSION (Leadership)	DESCRIPTOR	CAPABILITIES	MATURITY ASSESSMENT				
			REACTIVE	FORMAL	DEPLOYED	AUTONOMOUS	WAY OF LIFE
Customer focus	- The company is focused on deliverables for internal and external customers. Customer needs are above individual or group needs. Customer targets are more important than individual targets. - External Customer processes are designed and integrated with Company data availability and analytics. - Leader competencies include customer focus, digitization, and sustainability to develop new digital circular processes for them. - Customer evolves into a data provider and becomes part of the production digital loop.	CRM: Customer Relationship Management					
		SLA (service level agreement) & Customer Satisfaction					
		Leader competence framework					
		Value Stream Mapping					
Customer & supplier development	- DGL is developed for customers and suppliers. Systems integration is in place to achieve higher levels of efficiency through process communication (IoT) improvement and waste elimination. - Leaders are capable, knowledgeable, and have tools to develop DGL in their internal and external Customers and Suppliers. Leaders have clear role descriptions and authority.	Job descriptions					
		Skills assessment & training needs analysis					
Teamworking	- Leaders have straightforward organization and spans of control that guarantee employee coaching and development (ratio depends on the job complexity) - Leaders develop proper communication and transparency and have the social ability to make contacts. Robots are considered part of the team and an essential input for problem-solving and decision-making. - Leaders consider teams above individuals and design the organization structure with new technologies (e.g., IoT, AR, Big Data, Robots, system integration, cloud computing, cyber systems, sustainability, circularity, cascade use...)	Organizational Design and Organizational Charts					
		Internal Communication					
Personal stability	- There is a promotion policy, including horizontal promotions. Each position has minimum skills and stability to gain expertise and coaching. - Leader's evaluation system is based on soft skills, personal development, and hard skills. There is a skill-development matrix for leaders.	Promotions and Job Grades assignment process					
		Performance Evaluation					
Personal behavior	- Company culture is embedded in the daily work of the leader, creating role models. - Servant leadership style includes hansei (self-reflection), self-awareness, and assessment. Modesty & humility. Empathy. Credibility. Leaders promote professional relationships with the employees and are accessible. - The implementation of new technologies is done with collaboration and consensus with the team and puts the company's benefits above individual or team objectives. - Company leaders are experts in leading difficult conversations and managing conflict.	Leadership competence framework					
		Negotiation Skills					
Human-centric	- The organization has a succession plan process attached to an individual development plan. - Leader constantly develops and coaches his successor and the team. - Leader handles the digitalization strategy and sustainability effort with emotional intelligence and ethics	Difficult conversations and conflict management.					
Self-developing and learning	- The organization has a succession plan process attached to an individual development plan. - Leader constantly develops and coaches his successor and the team. - Leader handles the digitalization strategy and sustainability effort with emotional intelligence and ethics	Succession planning					
		Individual development plan.					
Empowerment	- Constant self-development and learning in a structured way, guided by a coach using available technologies (AR, digital twins...) - There is a specific leadership skills and competencies development plan. It includes social/personal/technical skills, new technologies (augmented reality, robotics, simulations...), sustainability, and inner/longer circularity principles.	Development and coaching					
		Skills assessment & training needs analysis					
Self-transcendence	- The company promotes team empowerment and fact-based decisions after data gathering and analysis. - Delegation of authority and accountability systems in place, measured and effective. Facts are separated from opinions for decision-making. - Data is shared across and not individual property. Autonomous robots, deep learning, and other systems provide data to the organization where/when it is needed or on demand.	Leader competence framework					
Servant	- The company promotes team empowerment and fact-based decisions after data gathering and analysis. - Delegation of authority and accountability systems in place, measured and effective. Facts are separated from opinions for decision-making. - Data is shared across and not individual property. Autonomous robots, deep learning, and other systems provide data to the organization where/when it is needed or on demand.	Team design and performance					
		Data based decisions.					
Experimental	- The company promotes team empowerment and fact-based decisions after data gathering and analysis. - Delegation of authority and accountability systems in place, measured and effective. Facts are separated from opinions for decision-making. - Data is shared across and not individual property. Autonomous robots, deep learning, and other systems provide data to the organization where/when it is needed or on demand.	Delegation of Authority.					
Continuous improvement and innovation	- Leaders set the true north and strive for perfection by visualizing greatness (self-transcendence). Leaders have physical and psychological strength and understand their contribution to the organization's future and influence on employees' personal and social lives. - Leaders are allowed and willing to take challenges with implementing new technologies and are not afraid of consequences. - Their critical role in the organization is reinforced and empowered. (Self-esteem, self-transcendence, and motivation).	Target setting and performance evaluation.					
		Leading by example.					
Zero-defects	- Leaders follow the servant model and are encouraged to be humble, trustful, listen to others, respectful, and fair. - Leaders use the new technologies development and sustainability principles to teach and develop their teams. (AR, Digital Twins, robots...)	Motivational tools.					
Process and lean expertise	- Leaders use data analysis, experimentation, hypothesis testing, and trial (Kata): Standardizing the results, communicating the improvements, and recognizing the employees. - New technologies enhance performance and increase productivity by designing experiments, simulations, big data, deep learning, artificial intelligence, or other suitable technologies. - Leaders balance technology implementation and sustainability to get the best for the organization.	Leadership versus Management					
		Development and coaching					
Problem-solving	- Organization promotes disciplined CI and Innovation through critical thinking, intellectual stimulation, and risk management. - System design includes new technologies (e.g., IoT, Big data and analytics, robots, simulations, cyber systems, and 3D manufacturing) and Circularity as critical elements. Results are more efficiency, less waste, higher productivity, and employees more engaged.	Process Management: Statistical process control, in control and capable					
		Kata: Experimentation, testing and trial.					
Genchi genbutsu	- There is a zero-defect mindset and tolerance for mistakes and failure when they happen. - Human error is dealt with based on intentionality and consequences through a progressive consequences policy. Learning is captured when mistakes happen. - There is a process to handle variability and error produced by the autonomous robots connected (IoT) and the consequences implemented.	Simulation techniques					
Target setting	- There is a process and knowledge to design, implement, and improve flow, takt time, and standardize work. - Leaders use augmented reality, big data, deep learning, artificial intelligence, robots, and other technology to support lean principles and improve process design, including circularities, sustainability, and productivity.	Innovation system (Continuous improvement, process improvements and system innovation)					
		Waste elimination and value stream mapping					
Targets deployment	- There is a process and knowledge to design, implement, and improve flow, takt time, and standardize work. - Leaders use augmented reality, big data, deep learning, artificial intelligence, robots, and other technology to support lean principles and improve process design, including circularities, sustainability, and productivity.	Error proofing (Poka-yoke)					
		Human error: Progressive consequences system					
Flow	- There is a process and knowledge to design, implement, and improve flow, takt time, and standardize work. - Leaders use augmented reality, big data, deep learning, artificial intelligence, robots, and other technology to support lean principles and improve process design, including circularities, sustainability, and productivity.	Design, operate and improve of processes (DA of Toyota)					
		Industry 4.0 tools design and implementation: Digitalization strategy					
Flow	- Leader masters scientific problem-solving, data analysis, root cause analysis, and simulation as a way of thinking. Teaches and guides others. - Information technologies are used for data analysis and decision-making. Production lines, robots, and cycles are connected (IoT), integrated, and constantly improved. To optimize the improvement cycle and cost, deep learning and simulations occur for every process/product redesign.	Scientific problem solving					
Flow	- Leaders are constantly on the shop floor as a philosophy for data-gathering, understanding the situation, circularity status, and coaching. Visual management and digital data visualization are key facilitators. - Data gathering implementation is done where the data is needed, avoiding central data controls as much as possible. A daily management system requires augmented reality, simulations, and deep learning (AI).	Shopfloor management					
		Daily Management system					
Flow	- There is a system to communicate its vision, mission, and values as long-term and short-term targets using digital information and quick data access. Targets for AI and autonomous robots are set separately and are part of the leader's responsibility. - Leaders recognize and reward achievements in real-time on the shop floor.	Observation skills					
Flow	- There is a system to communicate its vision, mission, and values as long-term and short-term targets using digital information and quick data access. Targets for AI and autonomous robots are set separately and are part of the leader's responsibility. - Leaders recognize and reward achievements in real-time on the shop floor.	Strategy development (Hoshin Kanri)					
		Target setting					
Flow	- Consistent and transparent target deployment and tracking (Hoshin Kanri). Reward and recognize success. - Autonomous robots, deep learning, AI, circularity, cascade use, and other new processes implemented are included in those targets. Responsibility for the outcome stays with the process owner.	Rewards and Recognition program					
Flow	- Leaders understand and use flow, system integration, stability, leveling, balancing, and inner and extended circles concepts. Manage flow rather than isolated operations with available tools like AR, Big data, cloud computing, simulation, deep learning, or digital twins. - Leaders improve processes from linear design to circular flow, where possible, using all the new technologies and tools and ensuring productivity and sustainability are maintained.	Strategy development (Hoshin Kanri)					
		Target setting					
Flow	- Leaders understand and use flow, system integration, stability, leveling, balancing, and inner and extended circles concepts. Manage flow rather than isolated operations with available tools like AR, Big data, cloud computing, simulation, deep learning, or digital twins. - Leaders improve processes from linear design to circular flow, where possible, using all the new technologies and tools and ensuring productivity and sustainability are maintained.	Continuous flow (kanban, pull system line leveling and balancing)					
		Process redesign (Toyota DNA)					

CHAPTER 6: DIGITAL GREEN LEAN IN PRACTICE: COMPARATIVE CASE STUDIES IN ALUMINUM MANUFACTURING

This chapter presents the third empirical study of this thesis, addressing Research Question 3: How do regional institutional contexts influence organizational capability development for Digital Green Lean, and what mechanisms facilitate this while maintaining operational excellence? The study employs a comparative qualitative case study design examining how two multinational aluminum producers, one operating under European regulatory-driven institutional conditions, the other within the Gulf Cooperation Council's leadership-driven environment, develop organizational capabilities for Circular Economy implementation within established Lean manufacturing systems. Using Gioia methodology and abductive analysis, the study identifies four aggregate capability dimensions and demonstrates that Lean manufacturing capabilities function as enabling platforms for Circular Economy adoption regardless of institutional context.

Chapter 6 is presented in its entirety as prepared for publication. Tables and figures retain the numbering used in the journal submission. Chapter 7 provides the cross-study integration and synthesis connecting these empirical findings with the DGL conceptual development study (Chapter 4) and the maturity model (Chapter 5), as outlined in the thesis structure described in Chapter 1.

Submitted for publication:

Gatell, I. S., & Avella, L. (under review). Institutional Contexts and Organizational Capability Development for Circular Economy: A Comparative Case Study in Lean Manufacturing

INSTITUTIONAL CONTEXTS AND ORGANIZATIONAL CAPABILITY DEVELOPMENT FOR CIRCULAR ECONOMY: A COMPARATIVE CASE STUDY IN LEAN MANUFACTURING

ABSTRACT

Integrating Circular Economy within Lean manufacturing requires new organizational capabilities without dismantling the operational disciplines that define competitive position. Yet comparative evidence on how different institutional environments shape this capability development process remains largely missing. This study examines two multinational aluminum producers, one operating under European regulatory-driven conditions, the other within the Gulf Cooperation Council's leadership-driven environment, using Gioia methodology and abductive analysis of 11 semi-structured interviews triangulated with site observations and documentary evidence. Four aggregate capability dimensions emerge from the data. What the data shows above all else is that Lean manufacturing capabilities function as enabling platforms for Circular Economy adoption regardless of institutional context, a result robust across structurally different institutional environments. We extend Dynamic Capabilities Theory by specifying which existing Lean capabilities drive CE transitions, and advance Institutional Theory by demonstrating that divergent pathways can produce equivalent integration outcomes.

Keywords: circular economy; lean manufacturing; dynamic capabilities; institutional theory; comparative case study; organizational capabilities

1. INTRODUCTION

The aluminum industry presents a productive paradox for studying Circular Economy (CE) transitions in manufacturing. Aluminum is 100% recyclable without quality loss, yet primary production accounts for approximately 2% of global greenhouse gas emissions (International Aluminium Institute, 2023). The gap between that circular potential and linear operational reality is not primarily a technical problem, it is an organizational one. Closing it requires manufacturers to develop new capabilities for environmental monitoring, material recovery, and closed-loop supply chain management within systems built around entirely different performance priorities.

Lean Manufacturing (LM) systems are the dominant organizational framework in high-volume process manufacturing, and they are precisely where this tension surfaces. Most typical Lean disciplines like waste elimination, standardization, just-in-time flow, continuous improvement are deeply embedded after decades of implementation. The question of whether and how CE integrates within established Lean systems, without eroding the operational excellence those systems provide, is among the most practically significant questions in contemporary manufacturing management (Sasso et al., 2025; Schmitt et al., 2021).

Research has made progress, but almost entirely within single institutional contexts. Studies of European manufacturing document regulatory-driven CE adoption (Bjørnbet et al., 2021; Kurdve & Bellgran, 2021); studies of emerging economies examine different drivers (Franco & Giannoccaro, 2025). What is missing is comparative analysis of how structurally different institutional environments produce different organizational capability development pathways for the same CE integration challenge. That absence matters because multinational manufacturers routinely manage CE transformation across multiple contexts simultaneously, with no comparative evidence base to guide them.

We address that gap through a comparative qualitative case study of two multinational aluminum producers: one operating under European regulatory-driven institutional conditions, the other within the Gulf Cooperation Council's (GCC) leadership-driven environment. Both are global industry leaders with more than twenty years of Lean experience and explicit CE commitments. Two research questions structure the inquiry. RQ1: How do regional institutional contexts influence the development of organizational capabilities for CE implementation in Lean manufacturing companies? RQ2: What stakeholder

configurations and organizational mechanisms enable this development while maintaining operational excellence?

The paper makes three interrelated contributions. It extends Dynamic Capabilities Theory (Teece et al., 1997) by identifying which specific Lean-embedded capabilities function as platforms for CE transitions and under what institutional conditions. It advances Institutional Theory (Greenwood et al., 2008) by showing that divergent pathways can generate equivalent CE integration outcomes, a form of institutional pluralism that challenges universal best-practice assumptions. And it offers manufacturing executives an empirically grounded comparative framework for context-sensitive CE transformation strategies. The remainder of the paper is organized as follows: Section 2 develops the theoretical framework; Section 3 describes the methodology; Section 4 presents the four capability dimensions; Section 5 discusses implications; Section 6 concludes.

2. THEORETICAL FRAMEWORK

2.1 Organizational Capabilities for CE Transitions

Dynamic Capabilities Theory establishes that organizations do not build new capabilities from scratch, but they reconfigure, extend, and redeploy what they already have (Barney, 1991; Teece et al., 1997). For CE transitions in Lean-mature manufacturers, this logic is promising. Lean systems cultivate capabilities that CE implementation demonstrably requires like systematic waste identification, process measurement discipline, cross-functional problem-solving, and a continuous improvement orientation. Recent empirical research confirms that Lean and CE are more complementary than conflicting (Sasso et al., 2025; Schmitt et al., 2021). The waste elimination logic of Lean, targeting operational inefficiencies “muda” within the production footprint, extends to the resource waste logic of CE, which targets material flows across product lifecycles.

The extension does not happen on its own, though. Reconceptualizing what waste means is a cultural and leadership challenge (Aftab et al., 2023; Lee et al., 2024). Green dynamic capabilities research confirms that environmental capabilities develop through the interaction of existing operational skills with new environmental understanding, mediated by leadership commitment, organizational culture, and stakeholder pressure. Castro-Lopez et al. (2023) demonstrate empirically that absorptive and adaptive organizational capabilities drive CE

adoption, with institutional pressures functioning as the primary trigger for capability mobilization across a large sample of manufacturing firms. Their findings are compelling, but the study examines a single national institutional context. What it cannot address is whether the capability-building logic holds when organizations operate simultaneously across divergent institutional environments. The Digital Green Lean (DGL) framework (Gatell & Avella, 2024b, 2024a) provides an integrated account of this transition, showing how organizations combine Lean foundations, Industry 4.0 tools, and CE principles. What Dynamic Capabilities Theory has not sufficiently addressed is the institutional dimension: identical organizational capabilities may manifest as very different CE adoption patterns depending on the institutional environment. Specifying that relationship requires Institutional Theory.

2.2 Institutional Contexts and Capability Development

Institutional Theory explains why organizations facing similar challenges develop different responses: regulatory frameworks, cultural norms, legitimacy structures, and knowledge ecosystems shape what responses are available, expected, and deemed successful (Bruton et al., 2010; Greenwood et al., 2008). For CE adoption in manufacturing, institutional environment actively shapes the capability development process defining which capabilities organizations prioritize, at what pace, and how they integrate with existing operational systems. Bag et al. (2022) confirm this relationship showing that coercive, normative, and mimetic institutional pressures stimulate eco-innovation, which in turn builds CE capability in manufacturing firms, a mechanism they ground jointly in institutional theory and the dynamic capability view. Their findings, however, are drawn from SMEs within a single emerging economy.

European manufacturers operate within comprehensive regulatory structures: EU Circular Economy Action Plans, mandatory material recovery targets, carbon reporting requirements, and stakeholder accountability mechanisms. These create compliance-oriented capability development pressures: organizations build systematic monitoring infrastructure, reporting competencies, and stakeholder management processes. The historical depth of these pressures matters; European CE frameworks trace to landfill taxes of the 1980s, meaning organizational capability development has been incremental and deeply embedded over decades. GCC manufacturers operate under structurally different conditions. National vision programs like UAE Vision 2030, Saudi Vision 2030 position CE as a competitive advantage and

national transformation priority rather than a regulatory requirement (Nasta & Cundari, 2024). Government functions as a strategic partner rather than regulator, creating capability development pressures oriented toward breakthrough innovation and rapid organizational mobilization. Understanding how these contrasting pressures translate into different organizational capability pathways while recognizing that both can produce successful CE integration, is the central analytical problem this paper addresses.

2.3 Lean Manufacturing and CE Integration

A persistent assumption in the research literature is that Lean and CE are fundamentally in tension: Lean optimizes operational throughput within existing system boundaries while CE demands reconceptualizing those boundaries to incorporate material loops and reverse logistics (Bjørnset et al., 2021). This tension is real at the level of specific operational decisions. At the level of organizational culture and capability, however, it is considerably weaker. Lean organizations have measurement discipline, process stability, cross-functional problem-solving, and continuous improvement orientation, precisely the organizational infrastructure CE implementation requires (Kurdve & Bellgran, 2021). Value Stream Mapping extends naturally to environmental impact assessment at each process step. Kaizen events focused on waste reduction extend to material recovery when leadership frames them that way. 5-Why root cause analysis applies equally to tracing material losses as to quality defects.

Kristoffersen et al. (2020) argue that digital technologies enable CE strategies in manufacturing through three mechanisms: resource traceability, data transparency, and process optimization. What their framework does not address is how existing operational capabilities shape the firm's actual ability to absorb and deploy these digital-circular mechanisms. The present study's empirical evidence suggests that Lean capability is not simply compatible with digital-CE integration; it is a structural precondition for it in process manufacturing environments.

The transfer mechanism, however, is not automatic, and understanding why it sometimes stalls is as important as understanding why it works. The critical conceptual leap Lean-mature organizations must make is recognizing that the boundary of the system changes when CE logic enters. Lean targets muda within the production footprint and waste that accumulates between process steps, in inventory buffers, or in defect rework. CE targets material loss across the product lifecycle, including what happens after the product leaves the factory gate.

Extending Lean logic to CE therefore requires extending the definition of the system being optimized: not just the plant, but the material flows it participates in. Organizations that have made this shift describe it consistently as a leadership and framing challenge, not a technical one.

A second complication is less obvious but equally consequential: Lean's emphasis on standardization creates a structural tension with the variability that reverse logistics and closed-loop supply chains introduce. Standardization reduces variation to eliminate defects; reverse flows introduce variation, in material quality, timing, and volume, that standard Lean control systems were not designed to absorb. Addressing this requires either adapting existing Lean tools to handle variability in incoming recovered materials or developing new measurement and governance capabilities alongside them. The organizations in this study that had progressed furthest in CE integration had done both: they retained Lean discipline at the production process level while building separate but compatible governance mechanisms for the reverse material flows that CE requires. This distinction, between which Lean capabilities transfer directly and which require structural extension, has not been adequately theorized in the existing literature.

2.4 Theoretical Propositions

The three perspectives converge on a set of theoretically grounded expectations that guide the abductive analysis. These are starting points that the data will confirm, qualify, or revise (Fereday & Muir-Cochrane, 2006). The propositions state what theory leads us to anticipate; the findings section reports what the data reveals.

P1: Regional institutional contexts determine the primary pathway through which organizations develop CE capabilities within Lean systems with regulatory environments producing compliance-oriented pathways and leadership-driven environments producing innovation-oriented pathways.

P2: Stakeholder configurations mediate the relationship between institutional context and capability development, with external stakeholder dominance producing systematic, accountability-driven capabilities and internal stakeholder primacy enabling rapid, vision-driven development.

P3: Existing Lean manufacturing capabilities function as enabling platforms rather than constraints for CE implementation, providing the measurement discipline, cultural orientation, and process infrastructure that CE capability development requires.

P4: Organizations develop context-specific capability configurations for CE implementation, shaped by the institutional pressures and stakeholder expectations of their regional environment.

P5: Successful CE capability development generates feedback effects on institutional contexts, with organizational innovations contributing to standard evolution and shifting legitimacy expectations over time.

3. RESEARCH METHODOLOGY

3.1 Research Design and Case Selection

The study employs a qualitative comparative case study design (Eisenhardt, 1989; Yin, 2018). The rationale is straightforward: the mechanisms through which regional institutional pressures translate into different capability configurations cannot be adequately captured through surveys or statistical proxies; they need to be observed in context, at depth, before they can be reliably measured.

Two multinational aluminum producers were selected through theoretical sampling aimed at maximizing variation on the primary dimension of interest, institutional context, while controlling for variables that could mislead interpretation (Käss et al., 2024). Both companies are global industry leaders with more than 7,000 employees, serve predominantly international customer bases (80%+), have more than twenty years of Lean manufacturing experience, and carry explicit CE commitments in their corporate sustainability strategies. The European company operates across Germany, France, the Netherlands, and Nordic countries under EU environmental policy frameworks. The Middle Eastern company operates in the GCC, where sustainability strategy is shaped by national vision programs rather than regulatory mandates. The aluminum sector is particularly well suited to this investigation: the combination of high Lean maturity, significant environmental pressure, and theoretically unlimited circular potential creates genuine organizational tension between established capability configurations and CE requirements.

This design carries no claims of statistical representativeness for ‘Europe’ or ‘the Middle East.’ The analytic logic is analytical generalization to theory (Yin, 2018): the cases are selected to illuminate mechanisms and relationships, not to estimate population parameters.

3.2 Data Collection and Triangulation

Eleven semi-structured interviews were conducted across both companies: six in Europe and five in the Middle East. Participants represented diverse organizational levels: one senior executive, two sustainability managers, four operations and plant managers, two Lean specialists, and two supervisors. The study ensures both strategic-level perspective (regulatory pressures, investor expectations) and operational-level perspective (day-to-day implementation, process integration) are represented. All interviews were conducted in person or via videoconference between May 2021 and August 2022, lasting 65–120 minutes (mean: 83 minutes). Member checking sessions with five key informants in late 2024, three European and two Middle Eastern participants, validated the analytical constructs and confirmed that the identified LM–CE integration mechanisms accurately reflected organizational realities (see Chapter 3, Section 3.5.5 for full protocol details).

Interview data were triangulated through corporate sustainability reports (2019–2024), site observations at production facilities, and internal CE initiative presentations. Site observations were particularly valuable: whether daily management boards had begun incorporating environmental KPIs alongside throughput metrics, whether gemba walks included environmental observation, and whether A3 problem-solving was being applied to material recovery questions all provided behavioral evidence of LM–CE integration that interview accounts alone could not supply. Thematic saturation was assessed iteratively; no new first-order codes emerged after the ninth interview, and the member checking sessions in late 2024 confirmed thematic and analytical closure.

3.3 Gioia Methodology and Abductive Analysis

Data analysis employed Gioia methodology (Gioia et al., 2013; Magnani & Gioia, 2023), which provides a transparent pathway from raw interview data to theoretical constructs. The methodology is explicitly inductive in its orientation to data. First-order analysis preserves informant language without theoretical imposition, while being theoretically informed in how second-order themes develop. This is precisely what abductive reasoning describes: moving

iteratively between theoretical expectations and empirical patterns, allowing each to revise the other (Fereday & Muir-Cochrane, 2006; Vila-Henninger et al., 2024).

Analysis proceeded through three stages: (1) first-order analysis preserving informants' language (68 codes emerged); (2) second-order theme development through constant comparison with the theoretical framework; (3) aggregate dimension development integrating themes into overarching constructs. MaxQDA 2024 supported systematic coding and comparison. A critical clarification: the propositions in Section 2.4 were not tested in a deductive sense. They were developed from theoretical analysis before fieldwork to structure what to look for. The abductive analysis then lets data confirm, qualify, extend, and in some cases revise theoretical predictions. The propositions presented reflect the theoretically refined versions emerging from this iterative process.

Rigor was established through comprehensive audit trails documenting analytical progression from first-order codes to aggregate dimensions. The second author reviewed coding decisions and theme development throughout, providing critical examination of interpretations. Member checking with five key informants validated interpretive accuracy (Lincoln & Guba, 1985). All participant identities and organizational affiliations are anonymized: European participants are coded EU1–EU6, Middle Eastern participants ME1–ME5.

To strengthen coding reliability, a subset of 20% of first-order codes was independently reviewed by a second researcher; disagreements were resolved through discussion until consensus was reached.

4. FINDINGS

4.1 Data Structure

Analysis of 68 first-order codes produced four aggregate dimensions capturing how regional institutional contexts shape organizational capability development for CE implementation in Lean manufacturers (see Table 1). The four dimensions are: (1) Regional Institutional Contexts, (2) Organizational Capability Development, (3) Stakeholder-Driven Transformation, and (4) Cultural Adaptation Processes. Together they characterize the mechanisms through which institutional environment translates into organizational capability configurations, the central analytical question of this study.

The four dimensions are organized to follow the analytical logic of the study rather than chronological sequence or organizational hierarchy. Dimension 1 establishes the institutional and strategic context that sets the parameters for everything that follows. Dimension 2 addresses the operational and technical capability configurations that emerge within those parameters. Dimension 3 captures the stakeholder dynamics that translate institutional context into organizational action. Dimension 4 examines how capability development ultimately becomes embedded in organizational culture and identity over time, the process through which CE transitions from program to way of operating. Together, these dimensions trace the full pathway from external institutional conditions to internal organizational transformation, which is precisely what both Dynamic Capabilities Theory and Institutional Theory predict but rarely examine empirically in combination. The comparative structure of each dimension allows the mechanisms of institutional influence to surface through contrast rather than description alone.

AGGREGATE DIMENSION	2ND-ORDER THEMES	REPRESENTATIVE 1ST-ORDER CONCEPTS
1. Regional Institutional Contexts	Regulatory-driven (Europe)	"Everyone has their energy consumption program per plant" (EU2). "Europe initiated CE back in the 1980s by the first landfill taxes" (ME2). "Yearly energy targets — we are working quite hard on that" (EU2).
	Leadership-driven (Middle East)	"We work very closely with the leadership of the country" (ME1). "The leadership pushes to make metal out of sun" (ME1). "We became the first company in the world to make metal out of solar energy" (ME1).
2. Organizational Capability Development	Digital-enabled circular practices	"Soon we will be linked to a database where they can see what we are consuming from water, electricity, everything" (EU2). "Management of change — not only for safety, but also for sustainability" (EU2).
	Lean-facilitated CE integration	"I do not see a conflict — why should there be conflict?" (EU4). "Kaizen events focus on waste reduction and resource efficiency improvements" (EU3). "Value Stream Mapping now includes environmental impact assessments" (EU1).
3. Stakeholder-Driven Transformation	Bottom-up cultural development	"We are building a culture of Regional Sustainability coordinators... for site-specific sustainability plans with a more bottom-up approach" (EU3). "The best way to develop tomorrow's leaders is to give them platforms to participate in CE projects" (ME1).
	Strategic corporate alignment	"We have a world roadmap; a European roadmap; and from that we pick what is best for us — tailor-made for every plant" (EU6). "We are adding one more string to our bow... a lens through which to see sustainability" (ME1).
4. Cultural Adaptation Processes	Regional cultural integration	"We know CE is a good concept we want to be part of" (ME2). "Our hospitality culture extends to caring for the environment for future generations" (ME5).
	Stakeholder value creation	European case: recycled aluminum with 75% post-consumer content; carbon footprint 88% below industry average; closed-loop customer return system. Middle Eastern case: 100% by-product recovery — "Our waste becomes somebody else's feed material" (ME3).

Table 1: Data Structure: Regional Contexts and CE Capability Development in Lean Manufacturers

Note. Analysis of 68 first-order codes across 11 interviews. EU = European participant; ME = Middle Eastern participant. Identities anonymized.

4.2 Dimension 1: Regional Institutional Contexts

4.2.1 Regulatory-driven implementation: the European case

The European case company develops CE capabilities through compliance-oriented processes structured by regulatory requirements and stakeholder accountability. Change does not originate primarily within the organization; it is initiated by external mandates and calibrated through reporting frameworks. One European plant manager captured the dynamic: “We have, of course, all targets from the top; there is a clear direction... everyone has their energy consumption program per plant” (EU2). The regulatory foundation has deep historical roots: “That is very much how Europe initiated a lot of CE back in the 1980s by the first landfill taxes” (ME2). Three decades of regulatory pressure have produced embedded monitoring and accountability capabilities. When new CE requirements arrive, the European case company has measurement systems, reporting functions, and stakeholder engagement processes already in place. Institutional path dependence is visible here in its clearest form: the regulatory pressures of the 1980s and 1990s set capability trajectories that have compounded over subsequent cycles rather than being displaced by them.

The practical manifestation is visible at the operational level. Plants carry individual energy consumption programs with annual targets connected to performance management. Digital monitoring infrastructure makes environmental performance visible in real time: “Soon we will be linked to an external database directly where they can see what we are consuming from water, electricity, everything” (EU2). This is a compliance capability, but also an operational capability. The data it generates then feeds improvement processes that are recognizably Lean in character.

4.2.2 Leadership-driven implementation: the Middle Eastern case

The Middle Eastern case company operates under structurally different institutional conditions, and the capability development process reflects that directly. The driving force is not regulatory compliance but alignment with national transformation agendas, specifically, the country’s Vision program, which positions CE adoption as competitive advantage and national priority. The relationship between the company and government is collaborative: “We work very closely with the leadership of the country; we are a very visible organization” (ME1). This institutional configuration enables organizational change at velocity that compliance-driven processes do not match. When leadership commits to a CE initiative, task

teams are formed immediately, resources mobilized, and implementation follows. The most striking illustration: "We became the first company in the world to make metal out of solar energy... we shocked people when they heard that we are going from high-intensity to low-intensity carbon products" (ME1). The capability profile that emerges differs from the European case in character as well as pace: where the European company has built deep compliance and monitoring capabilities over decades, the Middle Eastern company has built breakthrough innovation capability and rapid organizational mobilization through alignment with national transformation goals.

4.3 Dimension 2: Organizational Capability Development

4.3.1 Digital-enabled circular practices

Both case companies developed digital infrastructure enabling real-time environmental performance visibility, a prerequisite for the monitoring and accountability that LM–CE integration requires. In the European case, this capability developed in response to regulatory reporting requirements: mandates drove investment in monitoring systems, which then enabled environmental management beyond compliance. The digital capability extends beyond monitoring to operational decision-making. New equipment procurement now incorporates sustainability assessment alongside safety: "When we buy new machinery, we do a management of change, and it is not only management of change for safety, but also for sustainability" (EU2). Specific circular technologies have been deployed, including briquetting machines for manufacturing swarf recovery. What is recognizable here is Lean measurement discipline repurposed for environmental performance.

4.3.2 Lean-facilitated CE integration

What stands out most clearly across both case companies is that operational participants rejected the efficiency–CE conflict assumption entirely. Practitioners who have been working with both frameworks for years tend to see the relationship quite differently from how academic literature has characterized it. One European operations manager put it bluntly: "I do not see a conflict... why should there be conflict? It might not be understood enough to realize there is no conflict" (EU4). In practice, Lean tools function as CE implementation mechanisms. "Kaizen events focus on waste reduction and resource efficiency improvements" (EU3). "Value Stream Mapping now includes environmental impact assessments at each step of our processes" (EU1). Pull systems designed to reduce overproduction simultaneously

reduce material waste from excess inventory. Gemba walks have begun incorporating environmental observation alongside safety and quality checks.

The cultural dimension transfers equally well. "For me it is very important... we always say 70% people and 30% machines... involve people and engage people, and the rest will fly" (EU2). In the Middle Eastern case: "The whole language of the organization has begun to change, the whole philosophy... we launched a campaign against plastics" (ME1). Lean provides the cultural infrastructure with continuous improvement orientation, respect for people, and systematic problem-solving. CE transformation requires them, regardless of institutional context. This finding addresses P3 directly: established Lean capabilities function as enabling platforms for CE adoption in both cases.

4.4 Dimension 3: Stakeholder-Driven Transformation

4.4.1 Bottom-up cultural development

The stakeholder configuration analysis reveals how institutional context translates into organizational change mechanisms. European operations face external stakeholder dominance: regulatory bodies set mandatory targets, customers demand certified sustainable products, ESG rating platforms create reputational accountability, and trade unions participate in sustainability governance. Automotive customers "challenge us with respect to how the speed of certain processes needs to change" (EU6). Managing simultaneous external requirements demands systematic stakeholder management capabilities that become organizational competencies. Middle Eastern operations face internal stakeholder primacy where top management and government function as collaborative transformation agents: "We work very closely with the leadership of the country... we do not want to embarrass them" (ME3). This configuration enables organizational change through alignment rather than negotiation, at a pace external stakeholder-driven change cannot replicate.

Both companies developed bottom-up cultural change processes alongside top-down alignment. In the European case, this was formalized through regional sustainability coordinator networks: "We are building up a culture of Regional Sustainability coordinators that work with the sites... to have site-specific sustainability plans with more bottom-up approach" (EU3). In the Middle Eastern case, CE capability development was embedded within leadership development: "The best way of developing tomorrow's leaders is to give them platforms by which they can participate actively in CE projects" (ME1).

4.4.2 Strategic corporate alignment

Both organizations maintained tiered governance mechanisms to keep site-level CE capability development coherent with global corporate direction. The European company used a hierarchical roadmap structure: "We have a world roadmap; there is a European roadmap. And from the European roadmap, we must pick what was best for us — it must be tailor-made for every plant" (EU6). The Middle Eastern executive framed transformation as adding a new performance dimension: "I feel my generation were focusing more on productivity, financial, and safety. Now we are going to add one more string to our bow... a lens through which to see sustainability" (ME1). This framing, extension rather than substitution, explains how CE capability development proceeds without threatening the operational excellence identity that Lean organizations are understandably reluctant to put at risk.

4.5 Dimension 4: Cultural Adaptation Processes

Both case companies demonstrated that CE capability development ultimately expresses itself in stakeholder value creation beyond compliance. The European case developed recycled aluminum products with 75% post-consumer content and carbon footprints 88% below industry averages, establishing closed-loop customer systems: "If a light pole gets hit, you deliver it back to our cast house and you get a new light pole" (EU3). The circular loop is complete, commercially viable, and operationally embedded — no longer a sustainability program but a business model. The Middle Eastern case achieved 100% diversion of production by-products to local cement manufacturers, eliminating landfilling: "Our waste becomes somebody else's feed material. That is how we see Circular Economy" (ME3). Cultural understanding of CE in both contexts was similarly grounded, not abstract environmental principle but practical operational logic embedded in familiar manufacturing frameworks. Cultural variation within regions appeared in the data (Nordic plants engaging communities through transparency; German facilities applying engineering precision to CE measurement; French operations integrating CE with worker quality-of-life), though with less structural regularity than the between-region differences that are the primary focus of this analysis.

What the data reveal about the cultural embedding process itself is worth examining separately. In both companies, the transition from CE as an organizational program to CE as an embedded operational logic followed a consistent pattern: it required connecting circular

principles to performance metrics that already had organizational legitimacy. In the European case, this connection came through environmental KPIs appearing on the same daily management boards as throughput and quality metrics alongside the indicators that plant managers were already held accountable for. The symbolic significance of that placement proved as important as the data itself. In the Middle Eastern case, the connection came through language: reframing material by-products as inputs to adjacent industries transformed how operational teams understood their own outputs. "Our waste becomes somebody else's feed material" (ME3) is not simply a logistics arrangement; it is a redefinition of what the organization produces.

This cultural embedding process has a temporal dimension that the cross-sectional design of this study cannot fully capture, but the data contain traces of it. Participants in both companies described early CE initiatives as feeling like additions to existing work, something done alongside normal operations. Over time, and at different rates in the two contexts, CE vocabulary and logic began appearing in spaces where it had not been present before: procurement decisions, equipment replacement cycles, customer conversations, and talent development. The cultural shift is an ongoing work to fully internalize CE into organizational identity; however the direction of travel is clear, and the Lean foundation appears to be what makes that direction sustainable.

DIMENSION	EUROPEAN CASE	MIDDLE EASTERN CASE
Primary institutional driver	Regulatory compliance framework	National leadership vision program
Change velocity	Gradual, systematic, path-dependent	Rapid, transformational, goal-driven
Dominant stakeholders	External: regulators, ESG investors, customers, unions	Internal: top management, government partners
Capability focus	Systematic monitoring, reporting, compliance management	Breakthrough innovation, rapid mobilization
Lean–CE relationship	Lean tools extended for compliance	Lean mindset enables innovation
Cultural orientation	Compliance first; stakeholder accountability	National vision alignment; competitive advantage
Key outcomes	75% post-consumer content; 88% lower carbon footprint	100% by-product recovery; waste as industrial feedstock
Proposition alignment	P1 (regulatory), P2 (external stakeholders), P4	P1 (leadership), P2 (internal stakeholders), P4

Table 2: Cross-Case Comparative Analysis of CE Capability Development Pathways

Note. Both cases confirm P3 (Lean as CE enabling platform) and provide partial support for P5 (institutional feedback effects).

5. DISCUSSION AND THEORETICAL CONTRIBUTIONS

5.1 Proposition Evaluation

P1 — institutional contexts determine the primary CE capability development pathway — finds its clearest support in the data. The two cases differ not in how much CE capability they have developed, but in the organizational logic through which development occurred: one systematic and compliance-structured, the other rapid and vision-aligned. That difference in logic is consequential beyond pace and style. Compliance-structured pathways produce capabilities that are deeply documented, externally verifiable, and transferable across organizational units because regulatory accountability demands standardization. Vision-aligned pathways produce capabilities that are organizationally concentrated, leadership-dependent, and faster to mobilize because the driving force is aligned intent rather than external constraint. Both produce effective CE integration, but they produce different

capability profiles and understanding which profile an organization has matters for what it can do next.

P2 — stakeholder configurations mediate this relationship — is similarly well supported. The difference in who holds change authority (external regulatory bodies and ESG investors in Europe; top management and government partners in the Middle East) has direct consequences for both the type of capabilities developed and the pace at which development occurs. It also shapes how organizations learn. External stakeholder dominance creates a learning environment oriented toward benchmarking, reporting transparency, and cross-industry standard-setting. Internal stakeholder primacy creates a learning environment oriented toward experimentation, rapid iteration, and bold initiative. The two learning orientations are not interchangeable, and organizations transitioning between institutional contexts, multinationals managing operations in both, need to deliberately develop both rather than assuming that one transfers naturally to the other.

P3 — arguing that Lean capabilities function as enabling platforms — carries what is arguably the most practically significant implication of the study. The evidence from both companies is consistent and the pattern holds across two institutional environments that differ in almost every other respect, which gives confidence that it reflects something structural rather than contextually specific. Three Lean capabilities emerge as particularly consequential for CE transitions: measurement discipline, which provides the infrastructure for environmental monitoring without requiring entirely new systems; continuous improvement culture, which means CE targets are treated as problem-solving challenges rather than organizational disruptions; and cross-functional integration, which enables the supply chain, operations, and sustainability functions to coordinate on reverse logistics and material recovery without the conflicts that inhibit CE progress in organizations without that habit. What is striking is that all of these competencies are general organizational competencies that CE implementation happens to require. Organizations that have invested in Lean are, in this sense, inadvertently preparing themselves for CE transitions before those transitions are on the agenda.

P4 — organizations develop context-specific capability configurations shaped by the institutional pressures — is borne out by the comparative analysis in Table 2: the four aggregate dimensions appear in both cases, but their specific content and emphasis reflect the institutional pressures of each setting. This finding has a less obvious implication: context-

specificity does not mean context-confinement. The European company's compliance infrastructure creates capabilities like systematic measurement, third-party verification, and stakeholder reporting, that have strategic value in GCC markets as those markets mature toward greater regulatory formalization. The Middle Eastern company's innovation mobilization capabilities like rapid organizational alignment, vision-to-action translation, and breakthrough initiative design, that have strategic value in European contexts where regulatory compliance alone is becoming insufficient for competitive differentiation. The capability configurations that institutional context produces are not permanently bound to that context; they become portable assets when organizations understand what they actually are.

P5 — that successful CE capability development generates feedback effects on institutional contexts — receives qualified support. Both companies actively participate in shaping the institutional environments in which they operate, one through engagement with EU regulatory bodies and industry associations, the other through direct collaboration with national vision implementation. The European case company contributed to the development of sector-specific CE standards that subsequently became regulatory requirements its competitors had to meet. The Middle Eastern case company's solar aluminum initiative became a reference point in the national sustainability narrative, influencing how subsequent industrial policies were framed. These feedback effects are real, but establishing their directionality and timescale with confidence lies beyond what interview-based case data can support. Longitudinal research tracking how specific organizational innovations diffuse into institutional environments would be needed to test P5 more rigorously.

5.2 Theoretical Contributions

The study makes four interrelated theoretical contributions. The first extends Dynamic Capabilities Theory by specifying which organizational capabilities matter most for CE transitions in manufacturing. Teece et al.'s (1997) sensing-seizing-reconfiguring framework is powerful but does not specify which existing capabilities provide the most productive foundation for sustainability transitions, an important gap when the argument is that organizations should build on rather than replace their existing strengths. The data show that Lean manufacturing capabilities with process measurement discipline, cross-functional problem-solving, and continuous improvement orientation, are precisely those capabilities

that enable CE adoption. Organizations investing seriously in Lean are not merely improving operational efficiency; they are building an organizational foundation that makes CE transitions more tractable, even when CE is not the explicit intent.

The second contribution advances Institutional Theory by demonstrating institutional pluralism in CE capability development. Existing research has documented how institutional environments shape organizational responses without examining whether structurally different responses can produce equivalent outcomes (DiMaggio & Powell, 1983; Greenwood et al., 2008). The comparative evidence here shows they can: European compliance-oriented and Middle Eastern vision-oriented pathways both produce successful CE integration within Lean systems, generating equivalent outcomes through distinct organizational mechanisms. Divergent pathways need not imply divergent outcomes, a finding with broader implications for how institutional theory conceptualizes the relationship between context and organizational effectiveness.

The third contribution concerns the Lean–CE relationship. Much of the operations management literature has treated this relationship as inherently tension-driven. The data challenges this assumption at both operational and cultural levels. Lean tools extend naturally to CE implementation when leadership frames them appropriately, and the continuous improvement culture Lean produces provides exactly the conditions CE capability development requires. The relationship depends more on organizational framing than on any inherent technical conflict. The fourth contribution is analytical: the comparative design demonstrates that mechanisms connecting institutional context and organizational capability are not reducible to degree of environmental pressure or regulatory stringency. The GCC context is not simply 'less regulated than Europe' but it operates under a different legitimacy structure that enables genuinely different capability development dynamics.

Where the first contribution specifies which capabilities transfer, this third contribution explains the organizational framing mechanism through which that transfer occurs.

5.3 Practical Implications

For European manufacturing executives, the central implication is to invest in systematic compliance capability like measurement infrastructure, reporting competency, and third-party verification, as the foundation for competitive differentiation, not only for regulatory compliance reasons. In this study, organizations that built robust environmental monitoring

ahead of regulatory requirements consistently found themselves better positioned when the next regulatory cycle arrived. For GCC operations, the practical implication runs differently: government partnership and leadership alignment are genuine change management assets enabling organizational mobilization that compliance-driven environments cannot replicate. The challenge is building sufficient accountability and measurement infrastructure to sustain capability development beyond the initial vision-driven mobilization phase. For multinational executives managing CE transformation across multiple regional contexts simultaneously, which is the case described in both case companies, the actionable implication is to establish global performance targets and environmental commitments at corporate level while explicitly preserving regional autonomy in change mechanism design.

The sequencing of capability development matters as much as its content, and the two contexts suggest different sequencing logic. In European contexts, the evidence points to a compliance-first, differentiation-second sequence: organizations that built monitoring and reporting infrastructure in response to early regulatory requirements found themselves with data assets that could later be converted into lower verified carbon footprints, credible recycled content claims, and supply chain transparency that customers increasingly value. The implication for European executives is not simply to comply but to build compliance capability at a level of precision and verifiability that exceeds current regulatory requirements, because the next regulatory cycle will likely demand what the current one does not yet require.

In GCC contexts, the sequencing challenge is different and to some extent harder. The vision-driven mobilization that national programs enable is a genuine organizational asset as it creates momentum and alignment that compliance-driven environments struggle to replicate. The risk is that this mobilization phase, which is energizing and visible, is not followed by the slower, less glamorous work of building measurement systems, accountability structures, and process standardization that would sustain CE capability development after the initial ambition has been demonstrated. Organizations in the Middle Eastern context that have succeeded in sustaining CE progress beyond the first wave of innovation share a common pattern: they translated vision-level commitments into operational metrics with clear ownership, connecting the inspirational national narrative to the daily management systems that Lean practice had already made part of organizational life. That translation is where CE capability in vision-driven contexts either becomes durable or fades.

Finally, for organizations managing CE transformation across both contexts simultaneously, the practical challenge is governance design: how to hold the two pathways together without either collapsing into the other. The temptation to impose the European compliance architecture on GCC operations risks suppressing the innovation velocity that the GCC institutional context enables. The reverse is equally problematic. What works is a governance model with genuinely non-negotiable global outcomes and genuine regional flexibility in how those outcomes are pursued.

6. CONCLUSIONS, LIMITATIONS AND FUTURE RESEARCH

The central question this study set out to answer was how regional institutional contexts shape the development of organizational capabilities for CE implementation within established Lean manufacturing systems. What emerged from the comparative analysis was two structurally distinct pathways, regulatory-driven in Europe, leadership-driven in the Middle East, that converge on successful CE integration through different organizational mechanisms. Four aggregate dimensions capture how this works in practice: the regional institutional context establishes the primary organizational change logic; the capability development mechanisms translate Lean foundations into CE applications; the stakeholder-driven transformation processes reflect the contrasting configurations of influence in each setting; and the cultural adaptation processes embed CE into organizational identity over time.

Three conclusions deserve particular emphasis. The first is that Lean manufacturing capabilities are CE enablers, not barriers. The process measurement discipline, continuous improvement culture, and cross-functional problem-solving that Lean-mature organizations have built over decades transfer productively to CE when leadership extends the frame appropriately. The second is that institutional heterogeneity produces viable capability diversity: there is no single correct organizational pathway for CE adoption within Lean systems. Attempts to impose European compliance mechanisms in leadership-driven contexts, or vice versa, risk suppressing the very institutional advantages that each pathway offers. The third conclusion is perhaps the least comfortable for technically oriented manufacturing organizations: the Lean-to-CE extension requires cultural work and development as much as technical work. The most consequential challenge is

reconceptualizing what the organization is structurally optimizing for, and that is a leadership and cultural challenge that process redesign alone will not address.

These conclusions come with important caveats. The two-company sample enables analytical depth but restricts empirical generalizability: findings characterize capability development in two large, Lean-mature, multinational aluminum producers in specific sub-regional institutional environments. They should not be generalized to ‘European manufacturing’ or ‘Middle Eastern manufacturing’ as monolithic categories because both regions are institutionally and culturally heterogeneous in ways that a two-company study cannot capture. The aluminum manufacturing context may produce CE capability dynamics different from those in discrete manufacturing or other sectors. The cross-sectional design captures organizational capability at specific points in transformation journeys rather than tracking development longitudinally.

Several research directions follow naturally from this work. Multi-industry comparative studies examining how different operational contexts affect the Lean-CE capability development relationship would test the transferability of the enabling mechanism identified here. Longitudinal studies tracking capability development over five-to-ten-year periods would illuminate how regulatory-driven and leadership-driven pathways evolve as institutional contexts mature. Quantitative research testing the mediating role of stakeholder configuration and the moderating role of organizational flexibility, both theoretically specified here, would strengthen empirical foundations. Research in SME contexts, where resource constraints and stakeholder configurations differ in important ways from the multinational cases examined here, would extend the framework’s applicability.

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CHAPTER 7: CROSS-STUDY INTEGRATION AND DISCUSSION

INTRODUCTION TO THE DIGITAL GREEN LEAN FRAMEWORK AS AN INTEGRATED ORGANIZATIONAL CAPABILITY

The three empirical studies reported in Chapters 4, 5, and 6 addressed distinct research questions through different methods. Considered together, however, they tell a story that none of them tells alone. This chapter brings that story into focus. Its primary purpose is to show what the collective findings reveal about Digital Green Lean (DGL) that no single study could have uncovered and why that matters both theoretically and for practitioners working in process manufacturing. Among those collective findings, one stands out for its theoretical reach: the evidence developed across all three studies supports positioning DGL as the fourth evolutionary phase of Lean Manufacturing, specifically, the adaptation of Lean's operational logic for simultaneous digitalization and circularity, a claim that becomes fully defensible only when the conceptual, developmental, and empirical components of the research are considered together.

The synthesis also serves a second function built into the research design. Chapter 3 (Section 3.6.3) noted that cross-study integration acts as a quality check: coherent findings across methodologically independent studies strengthen confidence in each; incoherence would require investigation. The integration achieved here confirms that the three studies examine the same organizational phenomenon from genuinely complementary angles. Where Study 3's empirical observations align with the conceptual expectations generated in Studies 1 and 2, the alignment is analytically meaningful. Where divergences appear around institutional dimensions, they extend rather than contradict the framework.

The chapter is organized as follows. Section 7.1 traces DGL's theoretical development across the three studies, from initial conceptualization through maturity operationalization to empirical grounding. Section 7.2 examines the four integration challenges that surfaced consistently across all studies, analyzing what they reveal about the limits of single-paradigm thinking. Section 7.3 articulates the distinct theoretical contributions this thesis makes to Lean Manufacturing evolution, circularity transitions in operations, and organizational capability development. Section 7.4 translates these findings into practical guidance for manufacturing organizations. Section 7.5 provides integrated answers to the three research questions and summarizes the chapter.

7.1 FROM CONCEPT TO PRACTICE: THE EVOLUTIONARY JOURNEY OF DGL

The three studies trace DGL from the abstract proposition that **Lean Culture and Lean Leadership must transform when Industry 4.0 and Circular Economy enter the picture simultaneously**, to a structured, empirically grounded framework that organizations can assess themselves against. This progression was not predetermined; rather, it emerged iteratively as each study revealed gaps that the next was designed to address, following the research design logic outlined in Chapter 3 (Section 3.2.1).

7.1.1 Study 1: Establishing the Conceptual Foundation

The systematic literature review in Chapter 4 identified a gap that proved more consequential than initially expected: while extensive literature examined pairwise relationships between Lean and Industry 4.0 (Buer et al., 2018; Ciano et al., 2020), or between Lean and sustainability (Caldera et al., 2019), research addressing the three-way integration was virtually absent. This absence constituted not merely an empirical gap but a conceptual one: the literature lacked a framework for characterizing organizations that pursue Lean operational discipline, digital transformation, and circular resource flows simultaneously.

Study 1's primary contribution was establishing DGL as a conceptual category requiring its own theoretical treatment, rather than a straightforward combination of the three paradigms. The analysis showed that I4.0 and CE affect Lean Culture and leadership in ways that are neither uniform nor symmetrical. Some traditional Lean competencies require reconceptualization when real-time data streams and robotics create new forms of visibility (Buer et al., 2020). Others, particularly human-centric leadership, become more important when automation risks distancing leaders from frontline realities (Dombrowski & Mielke, 2014; van Dun et al., 2017).

More significant was the finding that CE disrupts Lean differently than I4.0 does. Industry 4.0 largely extends and digitizes existing Lean practices; Circular Economy challenges the linear throughput assumptions on which Lean and early I4.0 implementations rest (Chiappetta Jabbour et al., 2019). Chapter 2 (Section 2.5.3) had flagged the efficiency-versus-circularity tension theoretically. Study 1 confirmed its depth and asymmetry, which explains both why the research design required a dedicated empirical investigation of CE capability development in Study 3 and why the efficiency-circularity challenge consistently emerged as the most difficult of the four integration tensions across the thesis.

7.1.2 Study 2: Operationalizing Through Maturity Assessment

The maturity model development from Chapter 5 addressed the gap between conceptual understanding and practical application. Organizations gaining awareness of DGL requirements face immediate questions: Where do we currently stand? What capabilities must we develop? In what sequence should development occur? The conceptual framework developed in Study 1 could not, by design, answer these operational questions.

The maturity model's distinctive contribution is its integration logic (Gatell & Avella, 2024a). Rather than treating Lean, I4.0, and CE as three parallel capability trajectories, the model structures development around the interdependencies their integration creates. The seven dimensions defined (leadership vision and strategic alignment, continuous improvement capability, digital technology integration, CE practices, stakeholder management, organizational learning, and performance measurement) intentionally cut across concept boundaries. Because organizational capability manifests as cross-paradigm configurations rather than siloed attributes, the model's structure is designed to reflect that reality. This directly responds to Chapter 2's conceptualization of DGL as requiring leadership and cultural transformation that spans all three paradigms simultaneously (Section 2.5.2).

The five maturity levels (Reactive, Formal, Deployed, Autonomous, Way of Life) capture more than increasing complexity. They describe a transformation from experiencing DGL as an external requirement imposed by market or regulatory forces, through systematic capability building, to the point where DGL values are internalized as organizational identity. This trajectory mirrors the original Lean transformation journey described in Chapter 2 (Section 2.1) but now three cultural transitions, Lean, digital, and circular, must be implemented in parallel rather than one by one in sequence.

The sequencing of capabilities across levels reveals something that practitioners often resist accepting: foundational Lean disciplines (standardization, visual management, problem-solving) remain non-negotiable; I4.0 capabilities reliably emerge only after process standardization is sufficiently stable to benefit from digitization; and systemic circular capabilities (closed-loop design, reverse logistics and circular business models) appear consistently at Autonomous and Way of Life levels, after both Lean and I4.0 maturity are established. Study 3 corroborated this sequencing pattern empirically in two organizations.

7.1.3 Study 3: Grounding in Organizational Reality

Chapter 6 brought the conceptual framework and maturity model into contact with organizational complexity. The aluminum sector was deliberately chosen because it is technologically sophisticated, environmentally intensive, and operates across institutional contexts that create different circularity pressures and resource configurations. The two multinational producers selected offered maximum contrast on institutional context, European regulatory-driven versus Middle Eastern leadership-driven, while holding constant industry, organizational scale, Lean maturity, and stated sustainability commitments (Eisenhardt & Graebner, 2007).

The study's central finding was that capability development pathways are simultaneously universal and context specific. Both companies developed similar capability categories: strategic vision and commitment, operational integration mechanisms, stakeholder engagement systems, and learning and adaptation processes. In that sense, both the conceptual framework and the maturity model are valid. Yet the mechanisms through which those capabilities developed, the relative emphasis placed on different elements, and the sequence of development differed between the two contexts. The European company built its capabilities in response to increasingly stringent regulatory requirements, with external accountability driving transparency and systematic measurement. The Middle Eastern company built its capabilities proactively as competitive differentiators and elements of national vision delivery, with strong top-down leadership enabling rapid resource mobilization and experimentation.

Neither pathway is superior. Both delivered successful CE implementation within functioning Lean systems. But the contrast highlights a key implication: DGL is not a universal blueprint; it is a framework requiring contextual interpretation, consistent with the pragmatist philosophical stance adopted in Chapter 3 (Section 3.1).

Study 3 also confirmed that even organizations with strong Lean foundations and genuine circularity commitments struggle with specific DGL integration tensions. Both cases encountered difficulty managing the conflict between Lean efficiency optimization, which assumes process stability and minimal inventory, and circular resource flows, which introduce variability and require buffer stocks of returned materials. Both struggled to sustain employee engagement when circularity initiatives demanded behaviors that departed from established

Lean disciplines. These are not implementation failures; they are inherent structural tensions observed across organizational contexts, confirming the integration challenges theoretically anticipated in Chapter 2 (Section 2.5.3).

The methodological contribution of Study 3 warrants explicit attention in the cross-study integration. Applying Gioia methodology (Gioia et al., 2013; Magnani & Gioia, 2023) to DGL capability development provided a structured pathway from raw practitioner accounts to theoretical constructs, a pathway that is neither purely inductive nor deductive, but fundamentally abductive. The five theoretical propositions in Study 3 were developed from prior theoretical analysis before fieldwork, providing an initial structural frame; the abductive analysis then allowed the data to confirm, qualify, extend, and in several instances revise those expectations. The four aggregate capability dimensions that emerged from this process (strategic vision and commitment, operational integration mechanisms, stakeholder engagement systems, and learning and adaptation processes) carry empirical credibility precisely because they were not predetermined but iteratively negotiated between theory and evidence (Fereday & Muir-Cochrane, 2006; Vila-Henninger et al., 2024).

This abductive design also generates a specific form of cross-study validity. The three studies in this thesis embody complementary methodological orientations: Study 1 follows a deductive-inductive logic through systematic literature review, Study 2 operates deductively through normative model construction, and Study 3 employs abductive reasoning through comparative case analysis. They together constitute a methodological triangulation that reinforces the overall research design. The alignment between the capability dimensions derived from Study 3 and the culture and leadership categories identified deductively in Studies 1 and 2 is not trivial: it constitutes mutual reinforcement across methodologically distinct approaches. Studies 1 and 2 established what DGL requires analytically; Study 3 confirmed what organizations develop in practice when pursuing that integration. The convergence across a systematic literature review, a normative maturity model, and an abductively grounded comparative case study strengthens confidence in the DGL framework in ways that no single methodological approach could achieve alone.

7.1.4 The Synthesis: What Three Studies Together Reveal

Study 1 established what must change. Study 2 defined how change can be assessed and managed. Study 3 demonstrated why change mechanisms differ across institutional contexts.

The coherence of these three answers, each derived through different methods and empirical bases, strengthens confidence in the DGL framework.

Table 7.1 maps key themes across the three studies and shows where integrated insights exceed what any individual study could generate.

Theme	Study 1 (Ch. 4): SLR	Study 2 (Ch. 5): Maturity Model	Study 3 (Ch. 6): Case Studies	Integrated Insight
Core DGL constructs	19 competencies, 10 characteristics across 7 dimensions	7 dimensions, 29 subdimensions, 81 capabilities across 5 maturity levels	4 aggregate capability categories validated empirically	DGL framework with conceptual, operational, and empirical components: constructs define what, maturity defines how, cases show contextual why
I4.0-Lean relationship	I4.0 primarily extends Lean through digitization of existing practices	Digital capabilities emerge at Deployed level after Lean foundation	Not directly addressed	I4.0 enhances Lean but requires sequencing: stable processes before digitization; human judgment must be preserved alongside automation
CE-Lean relationship	CE challenges linear assumptions, creates asymmetric disruption vs. I4.0	Systemic CE capabilities only at higher levels (Autonomous, Way of Life)	Both cases struggled with efficiency-circularity challenges; created semi-autonomous structures	CE is the most disruptive paradigm for Lean; integration requires accepting suboptimization in service of system-level circularity
Leadership transformation	New competencies required: systems thinking, paradox navigation, stakeholder dialog	Leadership challenges differ by maturity level: foundational → integration → institutional	Both cases: leadership commitment as critical enabler; institutional entrepreneurship essential	Leadership must evolve continuously: not a one-time adjustment but ongoing development through maturity stages with institutional engagement
Cultural evolution	Lean cultural elements remain relevant but require expanded interpretation	Cultural transformation deepens progressively through maturity levels	Established Lean Cultures both enable and resist DGL transformation	DGL requires cultural deepening, not replacement: expanding existing values to encompass digital and circular dimensions
Institutional context	Not directly addressed	External engagement captured at higher maturity levels	European regulatory vs. Middle Eastern leadership-driven: different pathways, similar outcomes	Institutional contexts shape pathways not just pace; organizations engage in bidirectional institutional influence
Nature of DGL capability	Organizational rather than technical: depends on culture and leadership	Developmental and progressive: structured maturity pathway	Context-dependent and institutionally shaped	DGL is an integrated organizational capability that requires development across sequential pathways with institutional engagement

Table 7.1. Cross-Study Synthesis Matrix: Key Themes Across Three Studies and Integrated Insights Emerging from Their Combination

Reading across the columns reveals three patterns that none of the individual studies, considered separately, could have surfaced.

The most fundamental insight is that DGL is fundamentally about organizational capability, not technical systems. While I4.0 technologies and CE practices involve technical elements, successful DGL implementation depends on cultural characteristics, leadership competencies, and institutional navigation. Study 1 identified what those competencies and characteristics are (Gatell & Avella, 2024b). Study 2 showed that technical adoption without underlying capability development produces superficial implementation (Gatell & Avella, 2024a). Study 3 confirmed it empirically: both case companies had access to comparable technologies and CE practices, yet their implementation trajectories depended on cultural readiness, leadership commitment, and institutional positioning, not technical sophistication. This aligns with Chapter 2's framing of culture and leadership as core organizing concepts for DGL (Section 2.5.2) and with dynamic capabilities theory more broadly (Teece, 2007; Teece et al., 1997). Organizations can acquire technologies without achieving DGL if the organizational capabilities underneath them remain underdeveloped. The implication for resource allocation is direct: technology investments must be matched by investments in cultural change management, leadership development, and institutional engagement.

A second pattern concerns DGL development as simultaneously sequential and parallel, and managing that tension is itself a leadership challenge. The maturity model suggests an orderly progression from Lean foundation first, then I4.0 enablement, and then CE, reflecting genuine developmental logic. The case studies reveal, however, that organizations rarely have the luxury of following that sequence. European regulatory frameworks impose CE requirements regardless of I4.0 maturity. Middle Eastern national vision programs expected simultaneous progress across all dimensions. Leaders must maintain foundational Lean disciplines while building I4.0 and CE capabilities concurrently, accepting that development will be messier than the maturity model's levels suggest. The model remains valuable as a diagnostic and planning tool: organizations should use it as a compass rather than a timetable. Both case companies demonstrated that selective advancement in specific dimensions, driven by external pressure or opportunity, could coexist with continued development in others, always provided leaders actively tracked the interdependencies (Tortorella & Fettermann, 2018).

The third insight shows that DGL requires institutional leadership, not merely operational excellence. Both companies succeeded not only by building internal capabilities but by shaping the environments in which they operated, influencing regulatory development in Europe, and contributing to national vision implementation in the Middle East. Study 1's conceptual framework focused primarily on internal organizational competencies and did not anticipate this. Study 2's maturity model captured some external engagement elements at higher levels. Study 3 revealed that institutional leadership is not late-stage refinement but an ongoing practice relevant from early in DGL development. This finding extends DGL's implications beyond operations management into strategic management and institutional theory, and it has a direct practical consequence: DGL transformation cannot be accomplished purely through internal change. Manufacturing organizations must participate in shaping the regulatory, normative, and cognitive institutions that define what sustainability means and how it is measured (Battilana et al., 2009; Maguire et al., 2004).

7.2 INTEGRATION CHALLENGES: NAVIGATING TRIPLE PARADIGM TENSIONS

Chapter 2 anticipated five structural tensions from theoretical analysis: Process Visibility vs Algorithmic Opacity; Standardization vs Digitalization; Incremental Improvement vs Transformative Change; Efficiency vs Circularity; and Human Judgment vs Algorithmic Decision-Making. The empirical work did not invalidate that map, but it refined it. Two of those tensions, both located at the Lean-I4.0 interface, turned out to be difficult to separate in practice. Organizations did not experience the opacity of algorithmic systems and the erosion of human judgment as distinct problems; they experienced them as the same problem arriving through different doors. Sustaining process standardization while simultaneously preserving frontline judgment in increasingly automated environments proved to be a single, compound organizational challenge. Both tensions are therefore treated here as one: Standardization vs Digitalization. The empirical work also surfaced something the theoretical analysis had not anticipated. The cross-case comparison revealed how organizations frame circularity shapes capability development pathways in ways that go well beyond implementation style. This is a genuine fourth tension, not a variant of the others, and it could only emerge from comparing two organizations operating under structurally different institutional conditions. The four challenges analyzed in Sections 7.2.1 through 7.2.4 are therefore not a simplification of the

five theoretical tensions. They are a more organizationally grounded account of what DGL integration demands.

Theoretical Tension (Chapter 2)	Paradigms	Description	Operational Tension (Chapter 7)	Evolution
T1: Process Visibility vs Algorithmic Opacity	Lean – I4.0	Lean's problem visibility discipline conflicts with the opaque reasoning of algorithmic systems	O2: Standardization vs Digitalization	Merged
T2: Standardization vs Digitalization	Lean – I4.0 – CE	Lean stable standards conflict with I4.0 customization logic and CE variable material inputs	O2: Standardization vs Digitalization	Merged
T3 Incremental Improvement vs Transformative Change	Lean – I4.0 – CE	Lean's kaizen rhythm conflicts with the radical transformation speed that both I4.0 and CE require	O4: Short-term Performance vs Long-term Capability	Renamed and transformed
T4: Efficiency vs Circularity	Lean – CE	Lean optimization within defined boundaries conflicts with CE's systemic expansion of those boundaries	O1: Efficiency vs Circularity	Retained
T5: Human Judgment vs Algorithmic Decision-Making	Lean – I4.0	Lean's investment in frontline knowledge conflicts with I4.0's tendency to displace it algorithmically	O2: Standardization vs Digitalization	Merged
(not theoretically anticipated)	Lean – CE – Institutional	How organizations frame circularity — compliance or opportunity — produces qualitatively different capability pathways	O3: Regulatory Compliance vs Competitive Advantage	Emerged empirically

Table 7.2. DGL integration tensions: theoretical origins and empirical refinement

All three studies encountered integration challenges that deserve explicit analysis. These are not problems to be solved through better project management or cleaner implementation plans. They are inherent structural tensions arising from the fact that Lean, I4.0, and CE embody different organizational logics that cannot be fully reconciled (Smith & Lewis, 2011). Understanding them is as important for theory as it is for practice. The empirical evidence confirms the tensions anticipated in Chapter 2 while revealing how they manifest in organizations. Those tensions can be named as Efficiency versus Circularity, Standardization vs Digitalization, Regulatory Compliance vs Competitive Advantage and last, Short-term Performance vs Long-term Capability. This chapter 7.2 analyzes them individually from 7.2.1 to 7.2.4 and what the four of them collectively reveal (7.2.5).

7.2.1 Efficiency Versus Circularity: The Core Lean-CE Tension

Lean Manufacturing is built on eliminating waste, reducing variation, optimizing flow, and minimizing inventory (Shah & Ward, 2003; Womack et al., 1990). Circular Economy, while sharing the waste reduction vocabulary, introduces regenerative principles that can directly conflict with those efficiency objectives (Ellen MacArthur Foundation, 2013; Kirchherr et al., 2017). Chapter 2 (Section 2.5.3) identified this theoretically as the efficiency-versus-circularity challenge. The case studies made the tension operationally visible.

The European company's experience with aluminum scrap reintegration illustrates the dilemma well. Lean logic dictates minimal work-in-process inventory and tightly controlled material specifications. Circular logic requires accepting returned material of variable composition, holding buffer inventory to accumulate economically viable processing volumes, and redesigning processes to accommodate that variation. The company's solution was to create semi-autonomous circular material streams with different performance expectations, a workable response, but one that fundamentally challenges Lean's ideal of seamless end-to-end flow.

The Middle Eastern company ran into similar resistance when implementing product life extension programs. Lean thinking optimizes for standardized high-volume production. Life extension requires service capabilities, reverse logistics, and variable refurbishment processes, precisely the kinds of complexity that Lean traditionally seeks to eliminate (Guide & Van Wassenhove, 2009). The response there was organizational separation of circular activities into specialized units, which solved the immediate problem but created coordination challenges and sacrificed potential synergies between production and circular operations. Both solutions represent adaptations rather than resolutions.

Lean-CE integration likely requires accepting suboptimization in certain areas to achieve system-level circularity objectives, a fundamental challenge to Lean's efficiency logic. Study 1 anticipated this asymmetry theoretically (Gatell & Avella, 2024b). Study 2 reflected it by placing systemic circular capabilities at higher maturity levels, implicitly acknowledging that organizations need established Lean and I4.0 foundations before managing the complexity that circular resource flows introduce. Study 3 confirmed it empirically by documenting the organizational structures both companies developed.

The implications extend beyond individual firms. At industry level, the efficiency-circularity challenge suggests that sector-wide coordination mechanisms may be necessary to manage circular resource flows that organizations cannot optimize internally. Aluminum, with its high recyclability and established secondary material markets, is better positioned for such coordination than most sectors, yet both case companies still encounter challenges in material-quality management, reverse logistics, and customer-supplier alignment on circular practices.

7.2.2 Standardization Versus Digitalization: The Lean-I4.0 Tension

Industry 4.0 promises automated optimization, data-driven decision-making, and adaptive manufacturing. Lean emphasizes standardized work, stable processes, and human judgment informed by *gemba* observation (Liker, 2004). Chapter 2 (Section 2.5.3) framed this as the standardization versus digitalization challenge. The empirical evidence shows that the tension manifests in more specific and structural ways than that initial framing suggests. Study 1's literature review captured the theoretical debate: some researchers argue that I4.0 enables better Lean through enhanced visibility and control (Buer et al., 2020; Sanders et al., 2016); others warn that excessive automation undermines the human development essential to sustainable Lean Culture (Bittencourt et al., 2020). Study 2 addresses the tension through sequencing where stable standardized processes create the foundation for beneficial digitization. Study 3 confirmed this general sequence while adding a significant qualification: rather than a simple linear progression, both companies maintained a continuous interplay between standardization and digitization initiatives.

In each organization digitizing unstable processes generated data without insight: automated reporting of dysfunctional practices. Equally, organizations that over-invested in manual standardization missed digitization opportunities that could have accelerated improvement cycles. The effective pattern was continuous bidirectional adjustment: standardization informing digitization, and digitization revealing where standardization required strengthening, rather than one stage strictly preceding the other. The deeper challenge concerns human judgment in increasingly automated environments. The two producers struggled to sustain *gemba* discipline when digital dashboards made remote monitoring easy. Leaders who previously walked the shop floor asking questions began relying on digital reports, weakening the human connections that Lean Culture depends on (van Dun et al.,

2017). This is not a technology failure but a leadership adaptation problem, one that Lean scholarship has not yet fully addressed.

The workforce implications are equally significant. Lean develops problem-solving capability, process understanding, and collaborative improvement skills. I4.0 requires data literacy, technology integration, and analytical reasoning. DGL demands simultaneous dual-capability development rather than substitution: a combination of deep operational expertise and broad digital literacy that neither traditional Lean training nor standard I4.0 implementation programs typically develop (Tortorella & Fettermann, 2018). At the time of the study, neither company had achieved systematic dual-capability development across their workforce.

7.2.3 Regulatory Compliance Versus Competitive Advantage: The Strategic Positioning Tension

Another challenge that only became visible through the cross-case comparison in Study 3, concerns how organizations frame circularity within DGL. Chapter 2 did not explicitly anticipate this; it emerged from empirical investigation, illustrating why a multi-method design that reaches into organizational practice can generate insights beyond those available through theory building alone, clearly following an abductive method.

The European company approached CE primarily through compliance and risk management. Regulatory requirements (extended Producer Responsibility, carbon pricing and waste directives) positioned circularity as a constraint to be managed efficiently rather than an opportunity to be exploited (Delmas & Toffel, 2004). The Middle Eastern company, operating in the relative absence of stringent regulation, approached CE as competitive advantage and element of national vision delivery. That framing encouraged institutional entrepreneurship and generated innovations in circular business models and value capture mechanisms that compliance-driven implementation typically does not produce (Bocken et al., 2016). This is a question of organizational identity as much as it is of strategy.

Neither framing is inherently superior. Compliance-driven approaches ensure baseline performance and systematic risk management. Opportunity-driven approaches enable innovation but risk greenwashing without accountability structures. Both cases suggest that mature DGL implementation requires a dual framing—treating circularity as constraint requiring systematic management and as opportunity enabling competitive advantage (Campbell, 2007). That dual framing emerged progressively in both organizations: the

European company began recognizing competitive advantages emerging from its compliance-driven capabilities; the Middle Eastern company increasingly recognized the need for accountability structures to validate its innovation claims.

The framing also shapes internal dynamics in ways that organizations should anticipate. The European company's compliance framing facilitated resource mobilization through regulatory legitimacy but limited employee enthusiasm by positioning circularity as obligation. The Middle Eastern company's opportunity framing generated internal energy and innovation but created external skepticism about the depth of commitment behind voluntarily adopted practices.

7.2.4 Short-Term Performance Versus Long-Term Capability: The Temporal Tension

All three studies encountered tensions between immediate operational performance and long-term capability development. Chapter 2 framed this as the contrast between Incremental Improvement and Transformative Change, the difference in rhythm between Lean's disciplined kaizen logic and the more radical transformations that I4.0 and CE require. The empirical work added a temporal structure that theoretical analysis did not fully anticipate in practice: organizations experience this tension not primarily as a question of pace but as a question of accountability. The pressure to demonstrate short-term results consistently undermined the sustained investment that long-term DGL capability development requires.

Lean improvements generate relatively quick returns, creating reinforcing feedback loops that sustain transformation momentum. I4.0 investments require longer payback horizons, testing organizational patience before delivering measurable returns. CE transformations have the longest time horizons, with benefits often accruing to future periods rather than to the implementing organization in the near term (Geissdoerfer et al., 2017). This temporal misalignment produces planning and investment dilemmas that conventional performance systems are not well equipped to manage. The problem is not one of management will; it is one of management infrastructure.

Each company responded by creating organizational structures with explicitly different performance expectations for circular innovation: innovation groups, R&D collaborations, and pilot facilities insulated from quarterly pressure. The approach worked in protecting experimentation. However, transferring insights from protected spaces back into routine operations proved difficult in both cases. The boundary between experimentation and

operational integration requires active orchestration that neither company had fully systemized.

The deeper problem is that this remains a structural challenge for most organizations pursuing DGL: how to embed long-term capability building into day-to-day operations rather than isolating it in special programs. The European company made partial progress by embedding circular targets into annual business planning cycles. The Middle Eastern company experimented with parallel performance metrics like operational efficiency measured monthly and circularity capability measured quarterly or annually. Both represented genuine improvements, but neither fully addressed the underlying tension.

Human capital development is where the temporal tension is most critical. Building the cultural characteristics and leadership competencies identified in Study 1 takes years. Yet both case companies faced pressure from corporate headquarters and external stakeholders to demonstrate results quickly. The maturity model provides a realistic timeframe for expectation management, but aligning stakeholder time horizons to that timeframe is a practical leadership challenge that organizations pursuing DGL will encounter consistently.

7.2.5 What the Integration Challenges Collectively Reveal

Taken together, the four challenges suggest that DGL integration is less a convergence on a single unified practice and more an ongoing navigation of inherent dilemmas. Lean, I4.0, and CE embody different organizational logics, in other words efficiency, optimization, and circularity, that cannot be fully reconciled. Organizations that make genuine DGL progress are not those that eliminate these tensions, but those that learn to hold and work them productively.

This reframes what integration means in multi-paradigm organizational contexts. Rather than eliminating contradictions, integration involves making the dilemmas explicit rather than suppressing them; creating organizational structures that allow different logics to coexist and inform each other; developing leadership capability for ambiguity, paradox, and temporal tradeoffs; maintaining ongoing dialogue between paradigms rather than allowing one logic to dominate; and accepting localized suboptimization when it advances system-level objectives.

This characterization extends paradox theory (Smith & Lewis, 2011) by demonstrating its applicability to operational integration across three management paradigms. The specific

tensions identified here may manifest differently in other industries, but the structural pattern is likely transferable to other multi-paradigm integration challenges. For manufacturing organizations, this means that the discomfort of managing competing logic is not a symptom of poor implementation; it is an inherent feature of operating at the frontier of organizational transformation.

7.3 THEORETICAL CONTRIBUTIONS: ADVANCING THREE LITERATURE STREAMS

The thesis contributes to three interconnected literature streams: Lean Manufacturing evolution, circularity transitions in operations management, and organizational capability development in institutional contexts. Chapter 2 mapped the theoretical terrain across those streams. This section articulates what the integrated research adds to each and are contributions that only become visible through the cross-study synthesis.

7.3.1 Contribution to Lean Manufacturing Literature: The Fourth Evolution

Lean Manufacturing literature typically describes three evolutionary phases: (1) Toyota Production System development (1950s–1970s), (2) international transfer and adaptation (1980s–1990s), and (3) extension beyond manufacturing into services and knowledge work (2000s–2010s) (Holweg, 2007; Shah & Ward, 2003; Sunder et al., 2018; Womack et al., 1990). Each phase expanded Lean's scope in response to new organizational and competitive demands, a pattern that Holweg (2007) identifies as the defining feature of Lean's developmental logic and that this thesis extends to the digital-circular challenge. This thesis identifies and conceptualizes a fourth: Lean's adaptation for simultaneous digitalization and circularity. Three specific theoretical advances emerge from the integrated analysis.

Perhaps the most far-reaching reconceptualization this thesis proposes concerns how Lean's core principles must be interpreted when circular material flows disrupt the linear assumptions on which they were built. Traditional Lean assumes linear material flow from suppliers through production to customers (Womack et al., 1990). CE disrupts that directionality, creating reverse flows, loops, and cycles. This thesis demonstrates, through both conceptual analysis in Study 1 and empirical investigation in Study 3, that Lean principles remain applicable to circular systems but must extend from linear optimization to circular system design. I4.0 transforms the informational basis of Lean practices without invalidating

their logic (Buer et al., 2018). The maturity model captures this reconceptualization by structuring capabilities that retain Lean's operational discipline while accommodating digital and circular complexity.

The genchi genbutsu principle illustrates this clearly. Traditional interpretation insists on physical presence at the actual place where work occurs. Digital technologies raise questions that Lean literature has not resolved: does real-time video constitute genchi genbutsu? Do digital twin simulations substitute for physical gemba? The thesis argues, and the case studies confirm, that the essence of genchi genbutsu as direct, unmediated contact with operational reality remains valid; what requires rethinking is what counts as “direct” when digital interfaces mediate much of organizational perception. Both case companies found that leaders relying exclusively on digital dashboards lost critical contextual understanding. Those who combined digital monitoring with physical presence achieved the most effective oversight. This suggests a principle rather than a prescription: technology can mediate access but cannot replace the judgment that physical presence develops. The gemba is not a location. It is a practice of attention.

What Study 1 also revealed, and Study 3 confirmed, is a cluster of competencies that traditional Lean frameworks do not address. Study 1 identified competencies not typically emphasized in Lean literature (Seidel et al., 2017, 2019): systems thinking across multiple value cycles; stakeholder dialogue beyond conventional customer-supplier relationships; paradox navigation for managing inherent tensions between competing logics; and long-term perspective combined with short-term operational discipline. Study 3 validated their practical importance as both case companies identified weaknesses in these areas as constraints on DGL progress. These are not refinements of existing Lean Leadership competencies; they constitute a genuinely new competency cluster.

The cultural dimension of the fourth evolution is no less significant. Study 1's analysis of cultural characteristics showed that core Lean cultural elements named as respect for people, continuous improvement orientation and customer focus (Bortolotti et al., 2015) remain relevant in DGL contexts. However, their interpretation must expand considerably. Customer focus in DGL extends beyond immediate buyers to encompass users across product lifecycles, communities affected by operations, and societal stakeholders concerned with environmental impacts. Continuous improvement must incorporate innovation alongside incremental

efficiency enhancement. Study 3's comparative analysis documented both case companies working through this cultural expansion, with differing levels of success.

Together, these advances position DGL as a natural extension of Lean's evolutionary logic. Previous evolutions expanded Lean from Toyota to global manufacturing, and from manufacturing to services. The fourth evolution expands Lean from linear efficiency to circular sustainability. For practitioners, this means that decades of Lean investment are not obsolete in the face of digitalization and circularity requirements; they provide the foundation upon which DGL is built. For scholars, it means the extensive Lean literature remains relevant but requires systematic extension to address new dimensions that I4.0 and CE introduce.

7.3.2 Contribution to Circularity Transitions Literature: Fundamentals of Operational Transformation

The first and most counterintuitive contribution to circular transitions literature is that established Lean systems create enabling conditions for circular economy adoption rather than simply constraining it, if integration is approached consciously and with a clear understanding of the tensions this creates.

Circularity transitions research typically operates at macro level, examining how incumbent sociotechnical regimes transform or yield to niche innovations (Geels, 2011; Markard et al., 2012). Operations management contributes by examining firm-level circularity practices and performance (Dubey et al., 2019; Guide & Van Wassenhove, 2009). This thesis bridges these levels by examining the organizational foundations of circularity transitions within established operational excellence frameworks. Three advances emerge.

Lean systems do not simply coexist with circularity transitions; they actively shape them, in enabling and constraining ways that existing literature has not sufficiently addressed. Much research treats Lean and environmental sustainability as either independent or naturally aligned through waste reduction logic (Caldera et al., 2019). This thesis reveals a more complex dynamic. Lean excellence creates a capability foundation that can accelerate certain circularity transitions, but that same foundation can also constrain transitions that require accepting practices that run counter to established Lean disciplines. CE implementation in Lean organizations is not a matter of adding circular practices to a pre-existing Lean architecture; It requires selectively maintaining, extending, and at times intentionally departing from Lean logic. This finding suggests that circularity transitions in manufacturing

cannot be meaningfully analyzed independently of the operational systems that pre-structure organizational behavior.

Where macro-level transition theory describes outcomes without examining process, this thesis contributes a granular account of how specific capabilities develop in practice. Study 3's Gioia analysis (Gioia et al., 2013) showed that key specific capabilities do not emerge through enterprise-wide system implementations but through localized experiments that expand and connect over time. Both companies developed material flow transparency capabilities in this way. This process-level insight complements operations-management research that tends to focus on adoption outcomes while overlooking developmental mechanisms. The most practically consequential finding for CE literature is also the one most likely to frustrate managers seeking shortcuts. Much CE research focuses on business model redesign (Bocken et al., 2016; Geissdoerfer et al., 2017) or technical circularity solutions (Haas et al., 2015). This thesis demonstrates that successful circular transformation requires prior changes in organizational culture and leadership competencies. The finding that systemic circular capabilities emerge only at higher maturity levels has important implications: organizations cannot shortcut their way to circular business models without building foundational capabilities. Viewed through the Multi-Level Perspective (Geels, 2011), this suggests that circular niche innovations require not only technological readiness but organizational capability readiness. The DGL framework operationalizes this by specifying which capabilities are needed and how they typically develop over time.

The practical implications of this finding are elaborated in Section 8.2.2

7.3.3 Contribution to Capability Development and Institutional Context Literature: Bidirectional Institutional Influence

Organizational capability development research focuses on how organizations build dynamic capabilities for competitive advantage (Teece, 2007; Teece et al., 1997). Institutional theory examines how organizations reflect institutional pressures and conform to institutional logics (DiMaggio & Powell, 1983). This thesis contributes by specifying three bidirectional relationships between capability development and institutional context that circularity-transitions literature has not previously examined at this level of granularity.

The most direct contribution to institutional theory is the demonstration that context shapes developmental pathways, not merely pace. Existing research recognizes that institutional

environments influence whether and how quickly organizations adopt sustainable practices (Campbell, 2007; Delmas & Toffel, 2004). Study 3 goes further by showing that different institutional contexts generate qualitatively distinct developmental pathways that nevertheless lead to similar capability outcomes. The European regulatory-driven context produced capabilities through sequential compliance responses; the Middle Eastern leadership-driven context produced them through experimentation and proactive positioning. Both pathways successfully developed the four aggregate capability categories, but through different mechanisms, sequences, and organizational configurations. This suggests that capability development is more institutionally embedded than dynamic capabilities literature typically acknowledges. This thesis terms this finding institutional pathway equivalence: structurally different institutional environments can generate qualitatively distinct capability development pathways that nevertheless converge on equivalent organizational capability configurations, a result that extends both Dynamic Capabilities Theory and Institutional Theory beyond their typical treatment of context as a determinant of outcomes.

More unexpected was the evidence of bidirectional influence. Both case companies participated in regulatory development processes, industry standard-setting bodies, and national circularity initiatives. This was not peripheral activity; it was integral to capability development. By helping shape regulatory frameworks (European case) or contributing to national vision development (Middle Eastern case), they created more favorable institutional conditions for their own DGL trajectories. The concept of institutional entrepreneurship (Battilana et al., 2009; Maguire et al., 2004) captures this dynamic, and this thesis provides manufacturing-specific evidence of its operation in practice.

At the most granular level, Study 3's Gioia analysis traced the specific organizational mechanisms through which institutional pressures translate into capability development. Institutional theory often focuses on macro-level isomorphism without examining organizational response mechanisms (DiMaggio & Powell, 1983). The findings showed those mechanisms: the European company translated regulatory requirements into internal improvement targets; the Middle Eastern company translated national vision aspirations into competitive differentiators. Both companies used external reporting requirements from Global Reporting Initiative (GRI), Carbon Disclosure Project (CDP) and Task Force on Climate

Related Financials Disclosures (TCFD) as structuring devices for capability development, effectively letting accountability frameworks guide what capabilities to build.

7.3.4 Integrative Theoretical Contribution: The DGL Framework

Beyond contributions to individual literature streams, the thesis's central theoretical contribution is the DGL framework itself. Chapter 2 (Section 2.5) introduced DGL as a conceptual proposition focused on Culture and Leadership. The empirical studies in Chapters 4–6 provide the evidence base that transforms that proposition into a structured, empirically grounded framework.

The DGL framework brings together the conceptual constructs from Study 1 (10 cultural characteristics across three dimensions and 19 leadership competencies across four dimensions), the developmental logic from Study 2 (seven capability dimensions, 29 subdimensions, and 81 specific capabilities across five maturity levels), and the contextual adaptation mechanisms from Study 3 (four aggregate capability categories developed through institutionally shaped pathways). Figure 7.1 visualizes the framework's structure and interdependencies.

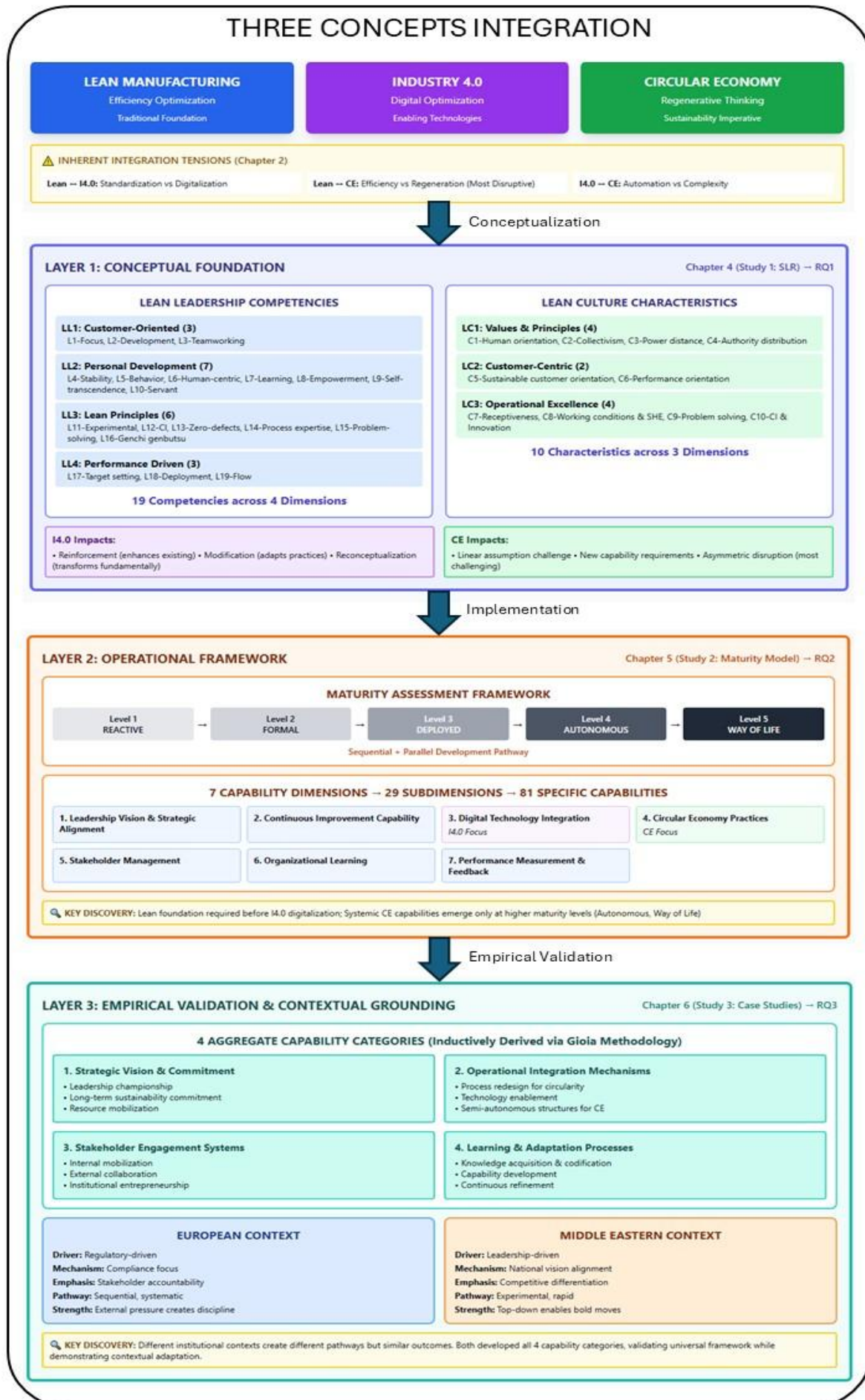
The framework provides several distinct types of value. Conceptually, it offers a unified vocabulary and analytical structure for a domain that was previously fragmented across multiple literature streams. Operationally, the maturity model's specificity, with 81 capabilities across five levels, gives organizations a diagnostic and planning tool for assessing their current state, identifying priorities, and planning developmental sequences grounded in organizational reality rather than abstract prescriptions.

What makes the framework distinctive as a scholarly contribution is that no prior instrument has addressed the three-paradigm integration challenge in a single, coherent measurement framework. Theoretically, the framework integrates and advances the Lean evolution, circularity transitions, and capability development literature, demonstrating their interconnection while articulating contributions to each.

The framework's boundary conditions should be stated clearly. The empirical grounding in aluminum production means that specific capabilities and developmental sequences may require adaptation for other manufacturing contexts, particularly discrete manufacturing. The institutional comparison covers European and Middle Eastern environments but not East

Asian or other significant manufacturing contexts. These are not limitations of the framework's contribution; they define the empirical starting point of departure for extension through future research.

The framework also illustrates a methodological point: the value of multi-method research designs for developing integrative organizational theory. The systematic literature review provided conceptual breadth. The maturity model methodology provided structured operationalization. The qualitative case studies provided empirical depth and contextual validation. No single method could have generated all three; the coherence across methods is a contribution (Eisenhardt & Graebner, 2007) to understanding how DGL research should proceed.



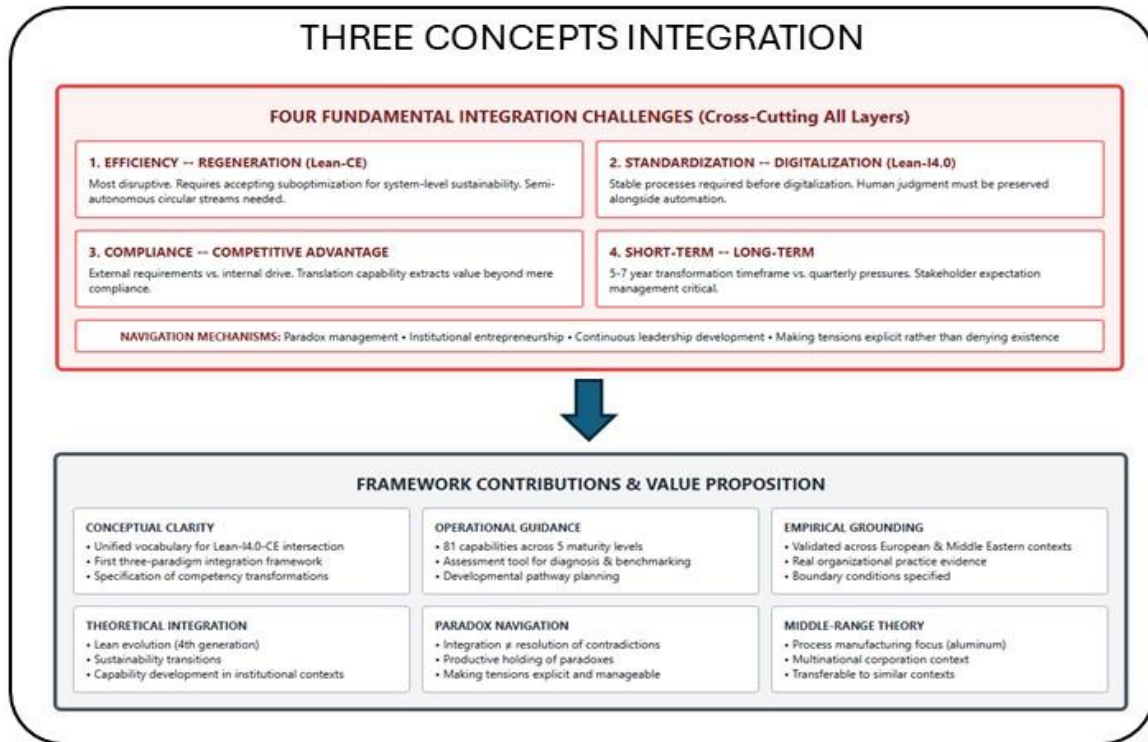


Figure 7.1. The Digital Green Lean (DGL) framework: From theoretical foundations to empirical grounding

The framework integrates three layers of evidence developed across the thesis. The conceptual layer (leadership competencies and cultural characteristics) derives from Study 1 (Chapter 4). The operational layer (seven capability dimensions, 29 subdimensions, and 81 capabilities across five maturity levels) derives from Study 2 (Chapter 5). The empirical layer (four aggregate capability categories and institutionally shaped development pathways) derives from Study 3 (Chapter 6). The integration challenges shown are cross-cutting findings corroborated across all three studies, and the arrows indicate the interdependencies among layers.

7.4 PRACTICAL IMPLICATIONS FOR MANUFACTURING ORGANIZATIONS

The theoretical contributions translate into practical guidance for manufacturing organizations pursuing DGL transformation. Five implications are identified, drawing on evidence from all three studies: (1) Start with Lean foundation, but do not wait for perfection, (2) Make integration challenges explicit and create holding structures, (3) Adapt to

institutional context while shaping that context, (4) Invest heavily in learning and knowledge management, and (5) Use maturity assessment for systematic development planning. They are presented not as a sequential checklist but as sustained organizational priorities requiring ongoing leadership attention.

7.4.1 Start with Lean Foundation, But Do Not Wait for Perfection

The maturity model suggests building Lean foundations before pursuing I4.0 and CE. The case evidence reveals that organizations face external pressures that do not respect that sequence. Both observations hold and reconciling them provides actionable guidance.

For organizations with limited Lean maturity, the priority is establishing basic disciplines like standardization, visual management and systematic problem-solving, before pursuing ambitious digital or circular initiatives. Both case companies reported that their most successful DGL implementations occurred in areas where Lean fundamentals were already solid. Premature digitization of unstable processes generates complexity without value. Circular initiatives in environments lacking process discipline create coordination challenges rather than circularity gains.

For organizations with strong Lean foundations, the evidence argues against waiting for Lean perfection before engaging in I4.0 and CE. Perfect Lean implementation is an unreachable target, and external pressures will not pause while organizations pursue it. The practical approach is parallel development with explicit monitoring of interdependencies: I4.0 tools can accelerate Lean improvement cycles; CE practices can extend Lean's waste reduction logic into resource circularity domains. The risk is losing Lean fundamentals during the transition, a pattern observed in both case companies, which requires deliberate countermeasures: regular audits of basic Lean practices, sustained leadership attention to fundamentals during periods of change, and visible celebration of successes that demonstrate integration across all three paradigms.

7.4.2 Make Integration Challenges Explicit and Create Holding Structures

Organizations typically attempt to minimize or deny challenges between competing priorities (Smith & Lewis, 2011). The DGL integration tensions resist suppression because they are structural, not managerial. A more effective response is to make these tensions explicit and

create holding structures, defined as arrangements that allow competing logic to coexist productively rather than forcing premature resolution.

The first practical step is acknowledging the efficiency-circularity tension openly. Both case companies found that naming the tension reduced organizational resistance and enabled more creative problem-solving than pretending it did not exist.

The second step involves creating semi-autonomous organizational spaces with explicitly different performance expectations for circular innovations. Both case companies used variants of this approach. Based on the evidence, four factors differentiate spaces that worked from those that became isolated: (1) clear performance expectations that differ from core operations; (2) regular integration mechanisms preventing the circular unit from becoming a silo; (3) formal knowledge transfer protocols from pilots to operations; and (4) resource protection that insulates the space from short-term financial pressure.

The third step is developing paradox navigation as an explicit leadership competency. Organizations should not only identify paradox navigation in competency frameworks but develop it through leadership programs that address; decision-making under genuine ambiguity; the combination of long-term perspective with short-term operational discipline; and system-level optimization that accepts local suboptimization. Evidence from both companies suggests that paradox-navigation capability develops primarily through practice rather than training, which has implications for how organizations design leadership experiences rather than classroom programs.

7.4.3 Adapt to Institutional Context While Shaping That Context

The case studies demonstrated that institutional context is not simply a backdrop against which DGL unfolds. It is an active shaping force, and in both cases, the organizations reciprocally shaped that context. The practical implications differ by institutional environment.

In regulatory-driven contexts, the evidence supports treating regulatory requirements not as constraints but as structuring devices for capability development. The European company found that proactive engagement in regulatory processes enabled it to influence how requirements were formulated in ways that rewarded existing capabilities and provided early-mover advantage in capability areas that regulations later made mandatory.

In leadership-driven contexts with weaker regulatory infrastructure, the evidence supports aligning DGL initiatives explicitly with national visions and strategic priorities, framing them as contributions to collective objectives rather than purely commercial activities. Organizations operating in such contexts also need to invest in building the stakeholder networks and knowledge-sharing infrastructure that regulatory frameworks provide automatically in more mature institutional environments.

Across all contexts, the evidence indicates that waiting passively for favorable institutional conditions is less effective than actively contributing to creating them. In both institutional environments, both organizations treated participation in industry associations, standard-setting processes, and multi-stakeholder circularity initiatives as an integral component of their DGL strategy.

7.4.4 Invest Heavily in Learning and Knowledge Management

All three studies identified organizational learning as a critical enabler and a persistent weakness. Both organizations had mature Lean knowledge management systems and grew I4.0 knowledge bases. Neither had an equivalent infrastructure for CE knowledge, and both paid for that asymmetry through repeated problem-solving cycles and missed cross-organizational learning opportunities.

The practical implication is that CE knowledge deserves the same systematic capture, codification, and dissemination that mature Lean organizations apply to Lean knowledge. This means creating structured repositories for circular implementation experiences including failures, which both case companies were reluctant to document systematically.

Cross-functional learning forums that connect Lean, I4.0, and CE expertise are essential, because capability gaps in DGL integration frequently occur at the interfaces between these domains rather than within any single domain. Both companies also found that external knowledge networks (universities, industry partners, technology providers, and other manufacturers), were critical for accessing leading-edge knowledge that internal development could not generate fast enough (Nascimento et al., 2019) given the pace of change in all three paradigms. The challenge is developing current knowledge while simultaneously building organizational learning capabilities, establishing mechanisms for continuous acquisition, integration, and application of new knowledge across all three DGL dimensions simultaneously.

7.4.5 Use Maturity Assessment for Systematic Development Planning

The maturity model developed in Study 2 and corroborated through Study 3 serves two functions that manufacturing organizations pursuing DGL can deploy directly: baseline diagnosis and development planning.

The baseline assessment should involve multiple organizational levels. A consistent finding across both assessments was the gap between leadership perception and operational reality across several dimensions. Assessments that include front-line staff, middle management, and senior leadership provide a more accurate picture and themselves generate valuable organizational dialogue about DGL priorities.

Development planning from the assessment should identify bottleneck capabilities rather than pursuing balanced improvement across all dimensions at once. Both case companies found that targeted investment in specific bottlenecks produced disproportionate DGL progress. Roadmaps should include explicit resource requirements, accountability assignments, and milestone definitions, using maturity level progression as a performance metric alongside conventional operational KPIs.

One qualification should accompany any organizational use of the model at this stage of its development. Constructed through systematic literature review and expert-informed design and examined and corroborated through two case organizations in the aluminum sector, the instrument has not yet been tested across a broad sample of manufacturing contexts. Organizations should therefore treat it primarily as a structured dialogue tool, a framework for generating informed internal conversation about DGL priorities and capability gaps. Both case companies found that the assessment process itself, the cross-functional discussions it prompted and the gaps it made visible, generated as much organizational learning as the resulting maturity profile. The metric should be reported at the same governance level as financial and operational performance, not treated as a sustainability reporting add-on.

7.5 INTEGRATED RESPONSE TO RESEARCH QUESTIONS AND CHAPTER SUMMARY

7.5.1 Integrated Answers to Research Questions

The three research questions were addressed individually by the three studies. Cross-study integration enables responses that draw on all three simultaneously, demonstrating how their

combined findings address the research aim more fully than any single study could. The theoretical framework established in Chapter 2 provides the interpretive context for these integrated responses.

RQ1: What is the impact of Industry 4.0 and Circular Economy on Lean Culture and Lean Leadership? I4.0 and CE affect Lean Culture and Leadership in fundamentally different ways, a pattern that becomes fully visible only when the three studies are read together. Study 1 identified the specific competencies and cultural characteristics affected, categorizing impacts as reinforcement, modification, or reconceptualization (Gatell & Avella, 2024b). Study 2 showed that these impacts manifest differently across maturity levels: basic Lean competencies retain relevance but their expression changes as organizations develop. Study 3 confirmed that organizations experience these impacts as operational realities, and that the efficiency-circularity tension (Lean-CE) proves consistently more challenging than the standardization-digitalization tension (Lean-I4.0). The integrated answer is that I4.0 primarily extends and enhances existing Lean practices through digitization, whereas CE fundamentally challenges the linear assumptions underlying both traditional Lean and early I4.0 implementations. Leadership must develop new competency clusters in areas such as systems thinking, stakeholder dialogue, and paradox navigation, while cultural transformation must expand established values to encompass regenerative alongside efficiency dimensions. The integration challenges anticipated in Chapter 2 (Section 2.5.3) are thus confirmed and extended by empirical evidence.

RQ2: How could leaders assess their competencies, attitudes, and behaviors to embrace I4.0 and CE while maintaining Lean Manufacturing excellence? The integrated answer is that leadership assessment for DGL reveals neither a fixed endpoint nor a linear checklist of adjustments. The maturity model developed in Study 2 enables organizations to locate their current position across five levels and seven dimensions, making visible an ongoing developmental process in which the nature of the challenge shifts as organization moves through maturity levels, and in which the required competency mix is never static. At the Reactive and Formal levels, the priority is consolidating foundational Lean disciplines because Study 3 confirmed that organizations lacking these cannot manage the additional complexity introduced by I4.0 and CE. Leaders at this stage must resist digitalizing before processes are stable and must protect Lean fundamentals from being displaced by circularity initiatives that

exceed the organization's absorptive capacity. At the Deployed and Autonomous levels, the assessed leadership challenge shifts toward integration management: sustaining the standardization-digitalization dialogue, building cross-functional capability for circular resource flows, and developing the paradox navigation skills that Study 1 identified as absent from traditional Lean frameworks. At the Way of Life level, the challenge is no longer building capabilities but embedding DGL values into organizational identity so that they persist beyond individual leadership tenures and external mandate cycles. Two findings cut across all maturity stages and resist strictly sequential framing. Human-centric leadership, centered on empowerment, servant leadership, and genuine respect for frontline judgment, proved consistently critical at every level in both case companies, not only in the early stages where Lean tradition places it. And institutional engagement, which the maturity model positioned as a higher-level capability, emerged in Study 3 as a practice that organizations must begin earlier than the model suggests: both companies found that waiting until Autonomous maturity to participate in regulatory development or industry standard-setting meant missing the window to shape the frameworks against which their own DGL progress would later be judged. Assessment of DGL leadership readiness must therefore be simultaneously inward-facing and outward-facing from the outset, capturing both internal capability development and active engagement with the institutional environments that define how DGL is measured.

RQ3: How do regional institutional contexts influence organizational capability development for DGL, and what mechanisms facilitate this while maintaining operational excellence? Study 3 demonstrates that institutional contexts shape not just the pace but the pathways of capability development. European regulatory-driven and Middle Eastern leadership-driven contexts produced qualitatively different development mechanisms leading to comparable capability outcomes across four aggregate dimensions. The integrated answer is that leading organizations do not merely respond to institutional contexts; they engage in institutional entrepreneurship, actively shaping the environment within which their DGL development occurs. Maintaining operational excellence during transformation requires explicit protection of Lean fundamentals through formal mechanisms while simultaneously building new capabilities. Neither regulatory pressure nor voluntary leadership initiative alone is sufficient; both contexts required complementary mechanisms to achieve comprehensive DGL development.

7.5.2 Chapter Summary

This chapter demonstrated that the three studies together generate an understanding of Digital Green Lean that exceeds the sum of their individual findings. The coherent integration across studies using different methods and examining different empirical settings confirms both the validity of individual findings and the strength of the research design, fulfilling the cross-study verification function outlined in Chapter 3 (Section 3.6.3). Where Study 3's empirical observations aligned with conceptual expectations from Studies 1 and 2, that alignment is analytically significant; where divergences appeared, mainly around institutional leadership, they extend rather than contradict the initial framework.

Four integration challenges emerged consistently: efficiency vs. circularity (core Lean-CE tension and the most fundamental); standardization vs. digitalization (Lean-I4.0 tension); compliance vs. competitive advantage (strategic framing tension, visible via cross-case comparison); and short-term performance vs. long-term capability development. These correspond to the challenges anticipated in Chapter 2 (Section 2.5.3) while adding empirical specificity and organizational texture. Successful DGL implementation does not resolve these tensions; it builds organizational capability to navigate them productively.

Theoretical contributions advance three streams: Lean evolution, a fourth evolutionary phase oriented to simultaneous digitalization and circularity; circularity transitions, organizational foundations of operational transformation within established excellence systems; and capability development in institutional contexts, through evidence of bidirectional institutional influence, basically organizations shaping the contexts that shape them. The integrative theoretical contribution is the DGL framework, offering conceptual clarity, operational guidance, assessment capability, theoretical integration, and empirical grounding as a middle-range theory for process manufacturing.

Three cross-cutting insights run through this chapter: (1) DGL is fundamentally about organizational capability, not technical systems; (2) DGL development is simultaneously sequential and parallel and requires ongoing leadership attention; (3) operating at the frontier of transformation requires active engagement with institutional environments, not only internal discipline.

Chapter 8 now draws the broader contribution of this thesis into a final synthesis, acknowledges limitations, and charts directions for future research.

NOTE: BIBLIOGRAPHY FOR THIS CHAPTER

The consolidated bibliography for all references cited in Chapters 1, 2, 3, 7 and 8 is included in Annex A. Chapters 4, 5, and 6 are published or publication ready papers and therefore retain their original bibliographies as published or submitted.

CHAPTER 8: CONCLUSIONS

Chapter 7 demonstrated that the three empirical studies, taken together, generate an understanding of Digital Green Lean (DGL) that exceeds the sum of their individual findings. This final chapter completes the thesis by articulating what that understanding means for theory, for practice, and for the research that should follow. Its purpose is different from Chapter 7's: rather than integration of empirical findings, this chapter synthesizes the Digital Green Lean framework providing clear answers to the research questions and presenting the integrated DGL model (Section 8.1), distills the thesis's theoretical contributions (8.2) and practical implications (8.3), acknowledges the principal limitations (8.4), proposes a structured agenda for future research (8.5), and closes with brief reflections (8.6).

8.1 SYNTHESIS: THE DIGITAL GREEN LEAN FRAMEWORK

8.1.1 Summary of Research Question Answers

Chapter 7 (Section 7.5.1) provided the detailed integrated answers to the three research questions. The following is a concise account, sufficient to ground the contributions and limitations discussed in sections that follow.

RQ1 — What is the impact of Industry 4.0 and Circular Economy on Lean Culture and Lean Leadership? I4.0 and CE reconfigure rather than supplement Lean Culture and Lean Leadership through three distinguishable patterns: (1) reinforcement of core human-centric and collaborative competencies that remain essential in digital and circular contexts; (2) modification of established practices like gemba, visual management, and continuous improvement, whose logic remains valid but whose specific expression must change; and the addition of competencies with no clear precedent in traditional Lean, including digital technology leadership and stakeholder orchestration across extended value cycles. Critically, the two concepts affect Lean differently: I4.0 largely extends existing Lean logic through digitization, while CE challenges the linear throughput assumptions underlying both traditional Lean and early I4.0 implementations. Organizations cannot address these impacts by adding I4.0 and CE elements to existing frameworks. The reconceptualization must run deeper than that (Chapter 4; Chapter 7, Section 7.5.1).

RQ2 — How could leaders assess their competencies, attitudes, and behaviors to embrace I4.0 and CE while maintaining Lean Manufacturing excellence? Assessment maps this developmental journey across five maturity levels (Reactive, Formal, Deployed, Autonomous, Way of Life) and seven integrated dimensions. Three transitions are consistently difficult: from Reactive to Formal, where organizational commitment becomes explicit and structural; from Formal to Deployed, where conceptual alignment must translate into operational practice; and from Deployed to Autonomous, where dependence on individual champion gives way to embedded organizational capability. Maintaining Lean excellence during transformation is not a matter of protecting existing practices from change but of applying Lean discipline — systematic problem-solving, standard-setting and continuous improvement to the transformation itself (Chapter 5; Chapter 7, Section 7.5.1).

RQ3 — How do regional institutional contexts influence organizational capability development for DGL, and what mechanisms facilitate this while maintaining operational excellence? Institutional contexts shape capability development through regulatory frameworks, stakeholder configurations, legitimacy dynamics, and knowledge ecosystems. Context is not deterministic. Organizations navigate institutional environments through compliance (meeting regulatory and social expectations), competitive positioning (leveraging context for advantage), or institutional entrepreneurship (actively shaping rules and norms), and the most capable organizations combine these approaches. Multinational organizations that operate across contrasting institutional contexts, in our case European regulatory-driven and Middle Eastern leadership-driven, can develop more comprehensive capabilities than organizations confined to a single environment, because heterogeneous pressures surface complementary capability requirements and reveal boundary conditions for DGL (Chapter 6; Chapter 7, Section 7.5.1).

8.1.2 The Integrated Digital Green Lean Framework

The DGL framework that emerges from integrating the three studies' findings constitutes a middle-range theory: abstract enough to apply across manufacturing contexts, concrete enough to provide actionable developmental guidance, and bounded enough to be explicit about where the evidence ends.

Its conceptual contribution is to specify how I4.0 and CE transform Lean Culture and Lean Leadership through reinforcement, modification, and the emergence of genuinely new

capabilities. Its operational contribution is to translate conceptual understanding into maturity levels, dimensions, subdimensions, and specific capabilities against which organizations can assess their current position and plan capabilities development and implementation. Its empirical contribution is to ground that structure in evidence from organizations navigating the integration and to show how institutional contexts shape development pathways.

The framework also acknowledges the navigation of the four structural tensions identified across all three studies: efficiency versus or circularity; standardization versus digitalization enabled customization and adaptivity; compliance versus competitive advantage; and short-term performance versus long-term capability. These are not implementation problems with available solutions. They are inherent features of pursuing three paradigms whose underlying logics differ. The framework's value lies partly in making those tensions explicit, naming them, tracing their sources, and building organizational capability to navigate them productively, rather than offering the false comfort of claiming they disappear at higher maturity levels.

8.2 THEORETICAL CONTRIBUTIONS

8.2.1 Lean Manufacturing Evolution: Fourth-Generation Lean

Lean scholarship has documented three evolutionary stages: a first generation focused primarily on tools and techniques; a second generation recognizing the centrality of culture and leadership; and a third generation beginning to address I4.0 integration (Holweg, 2007; Tortorella & Fettermann, 2018). What has been missing is a coherent framework for a fourth-generation Lean; one that integrates circularity alongside operational excellence and digitalization, treating the three not as sequential additions but as concurrent organizational demands with distinct and interacting logics. This research identifies and characterizes that fourth generation. The contribution is not the observation that Lean organizations must also address I4.0 and CE. The contribution is specifying what the integration actually demands: how core Lean concepts including *gemba*, visual management, and continuous improvement require reconceptualization rather than simple extension; how traditional assumptions about linear throughput, efficiency optimization, and standardization must evolve to accommodate circular flows and digitally enabled complexity; and what new competency categories like data governance literacy, cross-boundary orchestration for reverse flows, socio-technical change leadership emerge as essential yet absent in earlier Lean frameworks. The maturity model

provides the first comprehensive developmental structure for integrated Lean-I4.0-CE capability, organized around the interdependencies their integration creates rather than treating the three as parallel trajectories.

8.2.2 Sustainability Transitions: Foundations in Operations

Sustainability transitions have produced sophisticated analysis of macro-level sociotechnical dynamics like how incumbent regimes transform, how niche innovations diffuse, and how regulatory and market pressures reshape industrial systems. What has not produced enough is analysis of the organizational foundations through which those macro transitions happen inside manufacturing firms, particularly firms with established operational excellence frameworks.

This research addresses that gap by showing how organizations develop CE capabilities within existing Lean Manufacturing systems and how those systems condition both the sequence and the feasibility of change. The finding that strong operational excellence foundations can accelerate certain sustainability transitions while constraining others, a finding that challenges simplistic assumptions that Lean and sustainability are either naturally aligned or fundamentally opposed. The relationship is conditional and pathway-dependent. The research also identifies four aggregate capabilities both developed in case companies (strategic vision and commitment, operational integration mechanisms, stakeholder engagement systems, and learning and adaptation processes) and demonstrates that those dimensions evolve through institutionally shaped pathways, rather than universal implementation sequences. At the level of practical organizational action, the Gioia analysis specifies mechanisms by which organizations translate regulatory requirements or national-vision aspirations into internal capability-development targets, addressing a gap that macro-level transition theory does not resolve.

8.2.3 Organizational Capabilities in Institutional Contexts (Institutional pathway equivalence)

Dynamic capabilities theory examines how organizations build, integrate, and reconfigure competencies in response to changing environments (Teece, 2007). Institutional theory examines how organizational structures and practices reflect institutional pressures (DiMaggio & Powell, 1983). The two bodies of scholarship have remained largely separate because capability development research treats institutional context as background, and

institutional theory provides limited insight into the operational mechanisms through which pressures translate into capability changes.

This research bridges the gap in three specific ways. First, it demonstrates that institutional contexts shape not just the pace of capability development but the pathways, generating qualitatively different development mechanisms that lead to similar outcomes, thus advancing prior work from merely acknowledging contextual influence to specifying the mechanisms through which such influence operates. Second, it shows that leading organizations engage in institutional work that shapes the environments within which their own capability development occurs influencing regulatory frameworks, contributing to standard-setting, and participating in national sustainability initiatives. This bidirectional relationship between organizations and their institutional environments has been theorized (Battilana et al., 2009) but rarely documented at the level of specific operational practice in manufacturing contexts, thereby providing empirical grounding for a relationship typically discussed at a higher level of abstraction. Third, it identifies the micro-practices by which institutional pressures are translated into internal capability-building activity, clarifying how these pressures become actionable within day operations.

8.2.4 Integrative Contribution: Middle-Range Theory

Beyond contributions to individual literature streams, the DGL framework itself constitutes the thesis's primary integrative theoretical contribution. It provides conceptual vocabulary and analytical structure for a domain previously fragmented across Lean Manufacturing, circularity transitions, and organizational capability development literatures. It is middle range in the precise sense: not a high-level theory of organizational transformation, and not a narrow empirical generalization from two case studies, but a theoretically grounded framework with specified boundary conditions that generates testable propositions and can be refined through further empirical investigation. This positioning strengthens its usefulness by connecting theoretical rigor with empirical applicability, enabling it to serve both scholarly and practical purposes while also being honestly assessed against evidence rather than defended as abstract principle.

8.3 PRACTICAL IMPLICATIONS

8.3.1 Manufacturing Executives and Senior Leaders

Chapter 7 developed the DGL Framework visual (Figure 7.1) with integration challenges, mechanisms, and study layers. The most consequential practical insight from this research is that DGL transformation fails when treated as three parallel programs with separate champions, separate budgets, and separate performance metrics. The integration challenges documented across the three studies arise precisely from the structural tensions between the three paradigms' underlying logic; those tensions require active governance, not organizational separation.

Executives should position DGL explicitly as an integrated transformation, articulating a vision that connects operational excellence, digitalization, and circularity as mutually reinforcing while acknowledging the tensions between them openly rather than promising that integration eliminates them. The areas that made the most progress in the case studies were those whose leadership named the tensions explicitly and created space for dialogue about how to navigate them, rather than treating internal conflict between efficiency priorities and circular investment timelines as a management failure.

The structural mechanisms that matter most are cross-functional steering committees with real decision authority (not advisory or consultant roles); integrated performance dashboards that prevent siloed optimization by making trade-offs visible; escalation processes for resolving conflicts between paradigm logics; and resource allocation that funds integrated initiatives rather than forcing Lean, digital, and circular programs to compete for the same budget pools. Leadership modeling matters equally, companies need executives who participate in gemba walks examining both digital and physical processes, who raise circular material flow questions in business reviews, and who include DGL integration challenges in their own development goals, signaling organizational priorities through visible and consistent executive behavior.

Timeline management deserves specific attention. Lean improvements generate visible results within weeks. I4.0 investments mature over months to years. CE transformations develop over years and may deliver returns partly to future periods or to the broader value chain rather than to the implementing organization. Managing these three different temporal rhythms within a single organizational planning and accountability cycle requires explicit

structural protection for long-term DGL investments from quarterly performance pressure, establishing temporal governance as a necessary condition for sustained transformation rather than an optional leadership preference.

8.3.2 Operations and Plant Managers

For plant-level leaders, the most actionable finding is that the Lean capabilities already present in mature manufacturing organizations are the right foundation for DGL, provided they are extended deliberately rather than treated as fixed. A3 problem-solving applies directly to circular material flow challenges. Daily management disciplines apply to digital and circular metrics alongside traditional operational ones. Gemba walks should examine digital systems and circularity performance alongside physical process conditions. Continuous improvement of culture is exactly the orientation required for DGL experimentation where the barrier is not capability but habit.

Making integration tensions visible through standard management systems by displaying operational, digital, and circular metrics together in team performance boards; including DGL challenges explicitly in regular problem-solving routines; and documenting what works and what does not so organizational learning accumulates is the operational translation of the framework. The maturity model is most useful at plant level not as a score to be maximized but as a diagnostic tool for structured conversation and definition of a base line: where are we, where do we need to be, what is the specific gap holding us back, and what would it take to close it? Assessments that engage multiple organizational levels expose the gap between management perceptions of maturity and operational reality and consistently produce more accurate baselines and more useful development plans than top-down assessments alone.

Both case companies found that DGL progress was fastest in operational areas where Lean disciplines were already well established. This reinforces the maturity model's sequencing logic: the Lean foundation is not a prerequisite to be completed before DGL begins, but the foundation's strength in any given area directly determines how quickly I4.0 and CE capabilities can develop on top of it.

8.3.3 Policymakers and Regulators

The comparative case evidence offers several observations relevant to policy design. First, regulatory clarity and stability matter more than regulatory stringency in driving deep

organizational capability development. The European company benefited not from the intensity of requirements but from their predictability and consistency across planning horizons that enabled strategic investment rather than non-compliance minimization. Timelines that allow genuine capability development, transition support mechanisms, and frameworks that create competitive advantage for early movers rather than merely penalizing laggards emerge as more effective levers for long-term transformation.

Second, organizations that participated in regulatory development processes through contributing expertise, shaping implementation frameworks, and helping design what compliance looks like have developed more sophisticated capabilities and faster than those that waited for finalized requirements. Regulatory processes that create meaningful channels for practitioner involvement generate better regulations and better-equipped organizations simultaneously, reinforcing the value of co-production between regulators and industry experts.

Third, the knowledge infrastructure gap between institutional contexts is significant. European organizations benefited from dense ecosystems of consultants, research programs, peer networks, and industry standards that Middle Eastern organizations had to partly substitute through international partnerships and internal development. Policies that invest in knowledge infrastructure like research programs, industry association support, workforce development, or demonstration facilities generate more benefits than pure regulatory pressure alone.

8.3.4 Consultants and Technology Providers

The most consistent finding across both case companies regarding external support was that the most valuable partners, both consultants and technology providers, were those who engaged with the specific organizational context rather than applying generic frameworks, who built client capability rather than creating dependency, and who were honest about what their solutions could and could not deliver. This is easier to state as a principle than to endorse it as a business model, but the empirical evidence is clear: implementations that embedded capability in client organizations outlasted and outperformed implementations that required ongoing external management.

For I4.0 technology providers specifically, the sequencing insight from the maturity model has direct practical implications. Selling digital solutions into organizational areas where Lean

foundations are weak and where processes are unstable and problem-solving discipline is absent, generates data without insight and investment without return. The more durable commercial opportunity lies in helping organizations assess their DGL readiness before technology deployment, and in designing implementations that build on process stability rather than attempting to compensate for its absence.

8.4 LIMITATIONS

8.4.1 Methodological considerations

Each of the three empirical studies employed a primary method that carries inherent limitations. The systematic literature review in Study 1 depends on published knowledge and may underrepresent practitioner insights and failed implementations that do not reach academic publication. The maturity model in Study 2 was developed through conceptual logic and expert validation rather than large-scale empirical testing of its structure and performance relationships. The comparative case studies in Study 3 examined two organizations, which bring a depth that enables rich contextual understanding but limits statistical generalization.

The multi-method design across the three studies provides triangulation that partially offsets these individual limitations. The findings should be read as theoretically informed and empirically grounded propositions and not as definitive conclusions from large-sample quantitative research. This positioning is consistent with the methodological expectations for research on emerging, context-dependent organizational phenomena, where theoretical elaboration and mechanism identification take precedence over statistical inference.

8.4.2 Contextual Boundaries

The research focused deliberately on process manufacturing, specifically aluminum production, in large multinational corporations operating in European and Middle Eastern institutional contexts. Each of these choices was analytically motivated: process industries have characteristics that shape how Lean, I4.0, and CE manifest in distinctive ways; large multinationals have the organizational complexity and resources that make the integration challenge most visible and most consequential; and the European-Middle Eastern contrast provides institutional variation that illuminates how context shapes capability development pathways.

These choices also define the boundaries of confident generalization. Discrete manufacturing, services, and other process industries may exhibit different integration dynamics. SMEs face resource and capability constraints that make the maturity model's higher levels unrealistic without external support and may require substantially different frameworks. Asian, North American, Latin American, and African institutional contexts would likely reveal additional pathway variations not captured here. The conceptual frameworks (the identification of integration tensions, the capability categories, the institutional influence mechanisms) are more transferable across these boundaries than the specific implementation details and maturity level descriptions.

8.4.3 Data Collection Constraints

Case study research depends on organizational access and participant willingness. Both companies provided substantial access, but some constraints were unavoidable: commercially sensitive information was appropriately withheld; participation was concentrated at managerial levels, with limited frontline worker perspectives; and the retrospective nature of interview-based accounts means that participants reconstructed their organizational histories with more coherence than the actual experience may have contained. The multi-method data collection within each case provides triangulation that reduces but does not eliminate these effects. The findings represent participants' perspectives on DGL development, which may differ from those of other organizational stakeholders or from observers with different analytical lenses.

8.4.4 Analytical Choices

This research employed three theoretical lenses: dynamic capabilities (Teece, 2007), institutional theory (DiMaggio & Powell, 1983), and paradox theory (Smith & Lewis, 2011). They were selected because together they address the three central questions the research poses: how organizations build integrated DGL capabilities, how institutional contexts shape those development pathways, and how organizations navigate the structural tensions that integration generates. Each lens illuminates certain phenomena while leaving others less visible, and that is a limitation worth making explicit.

The resource-based view (Barney, 1991) was the most obvious alternative for the capability dimension of the research. It would have framed DGL capabilities as sources of sustained competitive advantage and directed analytical attention toward the conditions of rarity,

inimitability, and non-substitutability. That framing was considered and set aside because the research question is not which organizations gain competitive advantage from DGL, but how organizations develop DGL capabilities over time. Dynamic capabilities theory, with its emphasis on sensing, seizing, and reconfiguring in response to changing environments (Teece, 2007), fits that developmental and process-oriented question more precisely than a stock-based view of competitive resources does, what is analytically more suitable for explaining longitudinal capability formation.

For the institutional dimension, sociotechnical systems theory (Geels, 2011) offered an alternative framing that was seriously considered, particularly for analyzing how Industry 4.0 and Circular Economy disrupt and reconfigure existing manufacturing regimes. Its strength is precisely in analyzing regime-level transitions. Its limitation for this research is that it operates primarily at the system level and provides limited purchase on the organizational-level capability development processes that the comparative case studies were designed to examine. Institutional theory, with its attention to how regulatory frameworks, legitimacy pressures, and knowledge ecosystems shape organizational practice, fit the research design and empirical material more directly.

Complexity theory was considered as an alternative frame for the integration tensions that run across all three studies. It would have characterized efficiency-circularity and standardization-digitalization tensions as emergent properties of complex adaptive systems rather than as structural paradoxes requiring navigational capability (Anderson, 1999; Stacey, 1995). That framing was ultimately less useful for practitioners because it explains the persistence of tension without generating actionable guidance for leaders who must decide how to respond. Paradox theory's explicit attention to leadership practices and organizational routines for working with competing demands rather than resolving them connects more directly to the practical implications the research aims to produce. In this way, analytical insight translates more effectively into managerial guidance.

The DGL framework that results from these choices should therefore be understood as a theoretically informed conceptual construction that reflects the priorities of the research design and the questions posed, rather than a framework that would be identical under different theoretical assumptions. Alternative lenses would have produced different, and potentially equally valid, insights from the same empirical material.

8.4.5 Researcher Positionality

Twenty-five years of manufacturing industry experience provides genuine advantages for research of this kind: credibility with participants, ability to recognize and probe operationally significant details, and understanding of what the management challenges described feel like from inside an organization navigating them. It also creates risks deriving from preconceptions about which challenges matter most, possible privileging of senior management perspectives that align with prior professional experience, and potential blind spots about Lean's limitations in contexts where its logic does not translate straightforwardly.

Reflexivity practices like explicit acknowledgment of background, systematic data collection and coding protocols, transparent data presentation, member checking with participants, and sustained academic supervision, partially mitigate these risks. Researchers with different backgrounds would likely identify different patterns in the same empirical material, and that diversity of perspective is part of how the field advances. This research represents a practitioner-researcher perspective, with the strengths and limitations that combination entails.

8.4.6 Temporal Scope

The research captures DGL transformation at a specific historical moment — 2020 to 2025 — when I4.0 and CE remained emergent in most manufacturing organizations and when the management frameworks for addressing them were still being developed. Technology capabilities will evolve, regulatory frameworks will mature, and the specific integration challenges documented here may shift in character as organizations accumulate experience. The cross-sectional design also means that organizational development trajectories are inferred from point-in-time observation rather than tracked longitudinally, limiting understanding of how capabilities sustain over time and what factors determine whether early DGL progress compounds or stalls.

8.4.7 Confidence levels

These limitations point toward differentiated confidence in different aspects of the findings. The conceptual identification of I4.0 and CE impacts on Lean Culture and Leadership, the characterization of the four fundamental integration tensions, and the finding that institutional context shapes capability development pathways rest on convergent evidence across multiple methods and both empirical contexts and provides relatively high confidence.

The specific maturity level definitions, the precise capability counts (19 competencies, 10 characteristics, 81 maturity capabilities), and the specific mechanisms observed in the two case companies all require further empirical validation before generalization. Claims about applicability to SMEs, to contexts beyond process manufacturing, and about long-term capability sustainability are the most speculative, and provide the most cautious interpretation, reinforcing that confidence varies systematically across conceptual, empirical, and extrapolative dimensions of the research.

8.5 FUTURE RESEARCH DIRECTIONS

8.5.1 Theoretical Development

The maturity model developed in Study 2 was constructed through conceptual logic and expert validation. The most urgent research priority is developing validated measurement instruments for the 81 capabilities. Scale development procedures like item generation, expert review, pilot testing, and confirmatory factor analysis would enable the model to be tested across diverse manufacturing contexts and its relationship to operational performance outcomes to be examined quantitatively. This would also reveal whether the seven-dimension structure holds across different industries, whether the five-level progression reflects actual developmental sequences, and whether organizations at higher maturity levels achieve demonstrably better DGL outcomes.

8.5.2 Longitudinal Process Studies

Cross-sectional research can identify what organizational capabilities look like at a given moment but cannot directly observe how they develop over time. Longitudinal studies tracking manufacturing organizations through DGL transformation using real-time observation, repeated interviews, and critical incident documentation over three-to-five-year periods, would reveal developmental dynamics that point-in-time research cannot access. How do specific capability gaps constrain subsequent development? What triggers the transitions between maturity levels? Which early capability investments prove most consequential for long-term DGL progress? These questions require prospective longitudinal designs to answer reliably and enable researchers to capture path dependence, sequencing effects, and capability reinforcement mechanisms that remain invisible in static designs.

8.5.3 Contextual Expansion

The most immediate productive contextual expansions would address the boundaries identified in Section 8.4.2 and allow researchers to assess the stability of the DGL framework under markedly different institutional and cultural configurations. Discrete manufacturing contexts like automotive assembly, electronics, aerospace or even defense sector, would test whether the integration tensions and capability categories identified here transfer or require modification when continuous process characteristics are absent. SME investigation would examine whether the maturity model's higher levels are achievable without large-organization resources and what external support mechanisms most effectively substitute for internal capability. Geographic expansion into Asian manufacturing contexts would be particularly valuable given those regions' simultaneous leadership in I4.0 adoption, growing CE policy ambition, and deeply embedded Lean traditions that differ culturally from both the European and Middle Eastern contexts studied here.

8.5.4 Paradox Navigation as Organizational Capability

The finding that the four integration tensions require productive navigation rather than technical resolution has implications that this research has identified but not fully explored. What specific leadership practices enable productive navigation in DGL contexts? How does navigation capability develop over organizational time? Is it built through training, through accumulated experience with specific tension episodes, or through structural mechanisms that create repeated exposure to competing demands? What conditions cause the same tensions to generate creative organizational responses in some contexts and paralysis or destructive conflict in others? These questions are best addressed through longitudinal case studies with real-time observation of how organizations respond to specific integration challenge episodes.

8.5.5 Technology-Specific Integration Research

This research examined I4.0 as a cluster of technologies whose organizational implications were analyzed at a general level. As specific technologies mature and implementation experience accumulates, more detailed investigation of integration challenges becomes possible and valuable. How does the deployment of AI-driven process optimization interact with Lean's emphasis on operator problem-solving capability? What happens to gemba disciplines when digital twins provide comprehensive process simulation? How do

autonomous mobile robots change the human-machine collaboration patterns that Lean Cultures depend on? These technology-specific questions require research designs that examine implementation at sufficient operational depth to observe the cultural and leadership dynamics that general-level I4.0 research cannot reach.

More broadly, the emerging Industry 5.0 agenda, with its emphasis on human-centric, resilient, and sustainable manufacturing (European Commission, 2021) provides a natural policy and conceptual frame within which future DGL research can be positioned, extending the framework's relevance beyond I4.0's technological focus toward the broader organizational and societal challenges that the next industrial transition will require.

8.6 CLOSING REFLECTIONS

This thesis began with practical observation: manufacturing organizations worldwide are facing simultaneous transformation imperatives: operational excellence, digital capability, and circular sustainability, while the management literature has not provided adequate frameworks for navigating them together. What it has established, and what I am confident enough to state directly, is that integration is not merely additive, that the tensions between the three paradigms are structural rather than incidental, and that culture and leadership are the organizational dimensions on which integration succeeds or fails.

The DGL framework developed here is a beginning, not a conclusion. The maturity model's five levels describe a developmental progression that real organizations will travel in more complex ways than any model captures. The capability categories derived from the case studies reflect two specific institutional contexts and will require adaptation as research extends to other industries and geographies. The integration tensions identified across all three studies are likely to evolve in character as I4.0 technologies mature, as CE regulatory frameworks develop, and as organizations accumulate more experience with the specific trade-offs they require.

None of that weakens what the research establishes. Organizations can integrate operational excellence, digitalization, and circularity, the two case companies demonstrate it, imperfectly and incompletely, but genuinely. Integration requires organizational capabilities that are identifiable, assessable, and developable through structured attention over time. Institutional context shapes the pathways significantly but does not determine outcomes: organizations

that engage in their institutional environments actively, rather than simply adapting to them, systematically develop more comprehensive DGL capabilities than those that respond passively.

The four integration tensions defined as efficiency versus circularity, standardization versus digitalization, compliance versus competitive advantage, and short-term performance versus long-term capability, will not disappear at higher maturity levels. They are structures of the organizational terrain, not bugs in the implementation. Learning to navigate them productively, to hold competing analyses in tension without resolving them artificially, is itself the core leadership competency that DGL demands. It is also, not coincidentally, what the most effective manufacturing leaders I encountered over 25 years in the industry do, suggesting that paradox navigation is a foundational characteristic of mature industrial leadership rather than an optional skillset.

For researchers, the frameworks proposed here are intended as tools for further investigation rather than conclusions to be confirmed. Rigorous testing, critical engagement, contextual extension, and rejection in favor of better alternatives, are all forms of advancing the discipline. For practitioners, the frameworks are starting points for organizational diagnosis and developmental planning. Every organization navigating DGL transformation must find its own path through the specific institutional conditions, operational history, leadership capabilities, and cultural starting points it has.

The manufacturing organizations that successfully integrate operational excellence, I4.0, and CE will hold meaningful competitive advantages in the decades ahead. More importantly, they will demonstrate that industrial production and circularity are not opposed objectives requiring trade-offs, but complementary dimensions of organizational capability that reinforce each other when pursued with sufficient intelligence and commitment. That demonstration matters beyond any individual organization's competitive position. This research is offered as a contribution to making it more likely, with the hope that future research and practice will refine, challenge, and extend the foundations laid here.

NOTE: BIBLIOGRAPHY FOR THIS CHAPTER

The consolidated bibliography for all references cited in Chapters 1, 2, 3, 7 and 8 is included in Annex A. Chapters 4, 5, and 6 are published or publication ready papers and therefore retain their original bibliographies as published or submitted.

CAPÍTULO 8: CONCLUSIONES

El capítulo 7 puso de manifiesto que los tres estudios empíricos, considerados en su conjunto, generan una comprensión del Digital Green Lean (DGL) que supera con creces la suma de sus hallazgos individuales. Este capítulo final da cierre a la tesis precisando qué significa esa comprensión para la teoría, para la práctica directiva y para la agenda investigadora que debería abordarse en el futuro. Su propósito difiere del objetivo del capítulo 7: en lugar de integrar los resultados empíricos, se presenta la valoración directa del autor sobre lo que la investigación ha conseguido establecer, dónde residen sus límites y qué cuestiones permanecen aún sin resolver. El capítulo analiza la síntesis del marco DGL con respuesta a las preguntas de investigación (8.1); las contribuciones teóricas (8.2); las implicaciones prácticas (8.3); las limitaciones principales (8.4); propone las líneas de investigación futura (8.5); y finalmente da unas reflexiones de cierre (8.6).

8.1 SÍNTESIS: EL MARCO DIGITAL GREEN LEAN

8.1.1 Síntesis de respuestas a las preguntas de investigación

El capítulo 7 desarrolló con detalle las respuestas integradas a las tres preguntas de investigación. A continuación se presenta un resumen condensado, suficiente para fundamentar las contribuciones y limitaciones que se discuten en los apartados posteriores.

RQ1 — ¿Cuál es el impacto de la Industria 4.0 (I4.0) y la Economía Circular (EC) en la Cultura y Liderazgo Lean? La I4.0 y la EC no complementan sino que reconfiguran la Cultura y el Liderazgo Lean mediante tres patrones diferenciables: el refuerzo de competencias clave centradas en las personas y en la colaboración, que siguen siendo esenciales en entornos digitales y circulares; la modificación de prácticas consolidadas como el gemba, la gestión visual y la mejora continua, cuya lógica conserva su validez, aunque su definición concreta debe actualizarse en profundidad; y la incorporación de competencias sin precedente claro en el Lean tradicional, entre ellas el liderazgo tecnológico digital y la articulación de grupos de interés a lo largo de ciclos de valor extendidos. Conviene subrayar que ambos conceptos no afectan al sistema Lean de la misma manera: la I4.0 prolonga en buena medida la lógica Lean existente a través de la digitalización, mientras que la EC cuestiona los supuestos de flujo lineal de producción que sustentan tanto el Lean tradicional como las primeras implementaciones

de I4.0. Las organizaciones no pueden abordar estos impactos añadiendo simplemente elementos de I4.0 y EC a sus marcos actuales; sino que requiere una reconceptualización profunda. (Capítulo 4; Capítulo 7, Sección 7.5.1).

RQ2 — ¿Cómo los líderes pueden evaluar sus competencias, actitudes y comportamientos para incorporar la I4.0 y la Economía Circular manteniendo al mismo tiempo la excelencia en Lean Manufacturing?

La evaluación estructura este proceso de desarrollo a lo largo de cinco niveles de madurez —Reactivo, Formal, Desplegado, Autónomo y Forma de Vida— y siete dimensiones integradas. Tres transiciones resultan sistemáticamente difíciles: la de Reactivo a Formal, en la que el compromiso organizativo se vuelve explícito y adquiere estructura; la de Formal a Desplegado, en la que la alineación conceptual debe traducirse en práctica operativa real; y la de Desplegado a Autónomo, en la que la dependencia de un responsable individual cede paso a una capacidad organizativa plenamente integrada. Mantener la excelencia Lean durante la transformación no consiste en preservar las prácticas existentes frente al cambio, sino en aplicar la disciplina Lean con herramientas como la resolución sistemática de problemas, la definición de estándares, o la mejora continua, a la propia transformación (Capítulo 5; Capítulo 7, Sección 7.5.1).

RQ3 — ¿Cómo influyen los contextos institucionales regionales en el desarrollo de capacidades organizativas para el DGL, y qué mecanismos lo facilitan sin comprometer la excelencia operativa?

Los contextos institucionales moldean el desarrollo de capacidades a través de marcos regulatorios, configuraciones de grupos de interés, dinámicas de legitimidad y ecosistemas de conocimiento. El contexto, sin embargo, no es determinista: las organizaciones se relacionan con sus entornos institucionales mediante el cumplimiento normativo, la búsqueda de ventaja competitiva o el emprendimiento institucional, y las más avanzadas recurren a las tres estrategias de forma simultánea y deliberada. Las organizaciones multinacionales que operan en contextos institucionales de signo opuesto, en nuestro caso, un contexto Europeo orientado por la regulación y uno de Oriente Medio orientado por el liderazgo político, pueden desarrollar capacidades DGL más completas que las circunscritas a un único entorno, precisamente porque la heterogeneidad de presiones pone de relieve requisitos de capacidad complementarios y revela las condiciones de contorno del marco (Capítulo 6; Capítulo 7, Sección 7.5.1).

8.1.2 El Marco Digital Green Lean integrado

El marco DGL que emerge de la integración de los resultados de los tres estudios constituye una teoría suficientemente abstracta para resultar aplicable en distintos contextos manufactureros, suficientemente concreta para ofrecer a las organizaciones una orientación práctica para el desarrollo de capacidades, y suficientemente acotada como para ser honesta acerca del punto en el que la evidencia se detiene.

Su aportación conceptual reside en precisar cómo la I4.0 y la EC transforman la Cultura y el Liderazgo Lean mediante tres mecanismos que son refuerzo, modificación y emergencia de capacidades genuinamente nuevas y que actúan simultáneamente y se condicionan entre sí. Su aportación operativa consiste en traducir esa comprensión conceptual en niveles de madurez, dimensiones, subdimensiones y capacidades específicas frente a las cuales las organizaciones pueden calibrar su posición actual y planificar el desarrollo de capacidades de forma sistemática. Su aportación empírica fundamenta toda esa estructura en evidencia procedente de organizaciones que abordan la integración en la práctica, revelando cómo los contextos institucionales configuran los itinerarios de desarrollo.

El marco no elude las cuatro tensiones estructurales entre Lean, I4.0 y EC, identificadas de manera convergente en los tres estudios: eficiencia frente a circularidad; estandarización frente a digitalización; cumplimiento normativo frente a ventaja competitiva; y rendimiento a corto plazo frente a capacidad a largo plazo. No se trata de problemas de implementación que tengan una solución disponible, sino de características inherentes a la implementación simultánea de tres paradigmas cuyas lógicas de fondo divergen en aspectos esenciales. El valor del marco reside en parte en hacer explícitas esas tensiones: nombrarlas, comprender sus fuentes, y desarrollar la capacidad organizativa necesaria para gestionarlas de forma productiva, en lugar de ofrecer el falso consuelo de afirmar que desaparecen cuando se alcanza un nivel de madurez suficiente.

8.2 CONTRIBUCIONES TEÓRICAS

8.2.1 La evolución del Lean Manufacturing: el Lean de cuarta generación

La literatura académica sobre Lean ha documentado tres etapas evolutivas: una primera generación centrada principalmente en herramientas y técnicas; una segunda que reconoció el papel central de la cultura y el liderazgo como condición de sostenibilidad; y una tercera

generación que ha empezado a incluir la integración de I4.0 (Holweg, 2007; Tortorella & Fettermann, 2018). Sin embargo, no existía un marco coherente para el Lean de cuarta generación: aquel que integra la excelencia operativa con la circularidad y la digitalización, tratando los tres sistemas no como añadidos secuenciales, sino como exigencias organizativas simultáneas con lógicas propias e interacciones específicas.

Esta tesis identifica y caracteriza esta cuarta generación. La contribución no reside en constatar que las organizaciones Lean también deben atender a la I4.0 y a la EC, algo que ya se apuntaba en la literatura existente, sino que reside en especificar qué exige realmente esa integración: de qué manera conceptos nucleares del Lean, como el gemba, la gestión visual o la mejora continua, requieren una reconceptualización profunda y no una simple extensión; de qué modo los supuestos tradicionales en torno al flujo lineal de producción, la optimización de la eficiencia y la estandarización deben evolucionar para dar cabida a flujos circulares y a la complejidad habilitada digitalmente; y qué categorías de competencias emergen como imprescindibles sin que los marcos Lean anteriores las hayan identificado siquiera como categorías relevantes. El modelo de madurez proporciona la primera estructura de desarrollo integral para la capacidad Lean-I4.0-EC, organizada en torno a las interdependencias que su integración genera, en lugar de tratar las tres corrientes como trayectorias paralelas e independientes.

8.2.2 Transiciones hacia la Economía Circular: los fundamentos operativos

La literatura sobre transiciones hacia la Economía Circular ha generado análisis sofisticados de las dinámicas sociotécnicas a nivel macro: cómo se transforman los regímenes establecidos, cómo se difunden las innovaciones de nicho y cómo las presiones regulatorias y de mercado reconfiguran los sistemas industriales. Lo que esa literatura no ha desarrollado en suficiente medida son los fundamentos organizativos a través de los cuales esas transiciones macro se materializan dentro de las empresas de fabricación, en particular en aquellas que cuentan con marcos consolidados de excelencia operativa.

Esta investigación aborda esa carencia al revelar cómo las organizaciones desarrollan capacidades de EC dentro de sistemas de Lean Manufacturing ya existentes, y de qué modo esos sistemas determinan hasta dónde las organizaciones pueden llegar y en qué secuencia. El hallazgo de que unas bases sólidas de excelencia operativa pueden acelerar ciertas transiciones hacia la EC y, al mismo tiempo, constreñir otras, desafía las suposiciones

simplistas según las cuales el Lean y la EC se hallan naturalmente alineados o son fundamentalmente incompatibles. La realidad es más condicional y dependiente de los itinerarios de planifique la organización. La investigación también identifica las cuatro dimensiones agregadas de capacidad que ambas empresas desarrollaron, descritas como visión estratégica y compromiso, mecanismos de integración operativa, sistemas de implicación de grupos de interés, y procesos de aprendizaje y adaptación. Además, demuestra que esas dimensiones se despliegan a través de itinerarios condicionados institucionalmente, no mediante secuencias universales de implementación. A nivel de la acción organizativa concreta, el análisis Gioia desvela los mecanismos específicos mediante los cuales las organizaciones traducen los requisitos regulatorios o las aspiraciones de una visión nacional en objetivos internos de desarrollo de capacidades, algo que la teoría de la transición a nivel macro es estructuralmente incapaz de proporcionar.

8.2.3 Capacidades organizativas en contextos institucionales (equivalencia de itinerarios institucionales)

El enfoque de las capacidades dinámicas examina cómo las organizaciones construyen, integran y reconfiguran competencias en respuesta a entornos cambiantes (Teece, 2007). La teoría institucional, por su parte, analiza cómo las estructuras y prácticas organizativas reflejan las presiones del entorno institucional (DiMaggio & Powell, 1983). Ambas teorías han permanecido en gran medida separadas: la investigación sobre desarrollo de capacidades tiende a tratar el contexto institucional como un trasfondo dado a priori, mientras que la teoría institucional ofrece escasa comprensión de los mecanismos operativos concretos a través de los cuales las presiones externas se traducen en cambios de capacidades.

Esta investigación cierra esa brecha de tres maneras específicas. En primer lugar, demuestra que los contextos institucionales no solo condicionan el ritmo del desarrollo de capacidades, sino también sus itinerarios, generando mecanismos de desarrollo cualitativamente distintos que conducen a resultados similares; se trata de un hallazgo que extiende la investigación existente más allá del reconocimiento de que el contexto importa, avanzando hacia la especificación de cómo y por qué importa. En segundo lugar, muestra que las organizaciones líderes llevan a cabo un trabajo institucional activo que moldea los entornos en los que se desarrollan sus propias capacidades: influyen en marcos regulatorios, contribuyen a la fijación de normas y participan en iniciativas nacionales de sostenibilidad. Esta relación bidireccional

entre las organizaciones y sus entornos institucionales ha sido teorizada (Battilana et al., 2009; Teece, 2007), pero rara vez documentada a nivel de práctica operativa específica en contextos manufactureros; ello otorga a este hallazgo un alcance empírico que trasciende lo que la literatura suele ofrecer en forma de elaboración conceptual. Finalmente, la investigación identifica, por un lado, las prácticas concretas mediante las cuales las presiones institucionales se convierten en respuestas organizativas y, por otro, los mecanismos específicos de traducción que transforman los requisitos externos en actividades internas de desarrollo de capacidades. Contribuye así a esclarecer cómo esas presiones se vuelven operativas en el día a día de las organizaciones.

8.2.4 La contribución integradora: teoría de alcance medio

Más allá de las contribuciones que realiza a cada corriente de la literatura por separado, el propio marco DGL constituye la aportación teórica integradora principal de la tesis. Proporciona vocabulario conceptual y estructura analítica para un ámbito que hasta ahora se encontraba fragmentado entre la literatura sobre Lean Manufacturing, las transiciones hacia la circularidad y el desarrollo de capacidades organizativas. Es de alcance medio en el sentido preciso del término: no es una teoría de alto nivel sobre la transformación organizativa en general, ni tampoco una generalización empírica estrecha derivada de dos estudios de caso, sino un marco teóricamente fundamentado, con condiciones de contorno especificadas, que genera proposiciones contrastables y puede refinarse mediante investigación empírica adicional. Esta posición le permite servir tanto a fines académicos como prácticos, al tiempo que se evalúa frente a la evidencia disponible en lugar de defenderse como principio abstracto de validez incuestionable.

8.3 IMPLICACIONES PRÁCTICAS

8.3.1 Directivos y altos responsables en la industria manufacturera

El capítulo 7 desarrolló la representación visual del Marco DGL, con sus retos de integración, mecanismos y capas de estudio. La implicación práctica más relevante de esta tesis es que la transformación DGL fracasa cuando se aborda como si fuesen tres programas paralelos con responsables separados, presupuestos distintos y métricas de rendimiento independientes. Los retos de integración documentados en los tres estudios surgen precisamente de las tensiones estructurales entre las lógicas subyacentes de los tres paradigmas; tensiones que exigen una gobernanza activa, no separación organizativa.

Los directivos deberían posicionar el DGL explícitamente como una transformación integrada, articulando una visión que conecte la excelencia operativa, la digitalización y la circularidad como dimensiones mutuamente reforzantes, y reconociendo abiertamente las tensiones entre ellas, en lugar de dar por supuesto que la integración las elimina. En el estudio, las áreas que más progresaron fueron aquellas cuyo liderazgo nombró esas tensiones de forma explícita y creó espacio para el diálogo sobre cómo gestionarlas, en vez de tratar el conflicto interno entre las prioridades de eficiencia y los plazos de inversión circular como un síntoma de fracaso directivo.

Los mecanismos estructurales que resultan más determinantes son: los comités directivos transversales con autoridad real para tomar decisiones, y no meros roles asesores o consultivos; los cuadros de mando integrales que impiden la optimización por silos al hacer visibles los compromisos entre paradigmas; los procesos de escalada para resolver conflictos entre lógicas de distinto paradigma; y una asignación de recursos que financie iniciativas integradas, en lugar de obligar a los programas Lean, digital y circular a competir por los mismos fondos presupuestarios. El modelado del liderazgo importa en igual medida: las empresas necesitan directivos que participen en recorridos gemba en el taller examinando tanto procesos digitales como físicos, que planteen preguntas sobre los flujos de materiales circulares en las revisiones de negocio, y que incluyan los retos de integración DGL entre sus propios objetivos de desarrollo profesional. La organización interpreta esas señales con precisión, y su ausencia también.

La gestión de los horizontes temporales merece atención específica. Las mejoras Lean generan resultados visibles en cuestión de semanas. Las inversiones en I4.0 maduran a lo largo de meses o años. Las transformaciones de EC se desarrollan durante años y pueden generar retornos que, en parte, se materializarán en periodos futuros o recaerán sobre la cadena de valor en su conjunto, más que sobre la organización que las acomete. Gestionar estos tres ritmos temporales distintos dentro de un único ciclo organizativo de planificación y rendición de cuentas exige una protección estructural explícita de las inversiones DGL a largo plazo frente a la presión trimestral del rendimiento: no como preferencia de liderazgo, sino como condición estructural de la transformación.

8.3.2 Gerentes de operaciones y de planta

Para los responsables de planta, el hallazgo más útil es que las capacidades Lean ya presentes en organizaciones maduras constituyen la base adecuada para el DGL, siempre que se amplíen de forma deliberada en lugar de tratarse como un activo fijo e intocable. La resolución de problemas mediante el método A3 es directamente aplicable a los retos del flujo circular de materiales. Las disciplinas de gestión diaria son igualmente válidas para métricas digitales y circulares junto con las operativas tradicionales. Los recorridos gemba deberían examinar los sistemas digitales y el desempeño en circularidad al mismo tiempo que las condiciones físicas del proceso. Y la mejora continua de la cultura es exactamente la orientación que el DGL requiere para la experimentación, donde la barrera no reside en la falta de capacidad técnica, sino en la inercia del hábito.

Este marco se traduce a nivel operativo en hacer visibles las tensiones de integración a través de los sistemas estándar de gestión mostrando métricas operativas, digitales y circulares conjuntamente en los tableros de rendimiento de los equipos, incluyendo explícitamente los retos DGL en las rutinas habituales de resolución de problemas, y documentando lo que funciona y lo que no para que el aprendizaje organizativo se acumule. El modelo de madurez es más provechoso a nivel de planta, no como una puntuación que hay que maximizar, sino como una herramienta de diagnóstico para una conversación estructurada: ¿dónde estamos?, ¿dónde necesitamos estar?, ¿cuál es la brecha concreta que nos frena?, ¿qué requeriría cerrarla? Las evaluaciones que involucran a múltiples niveles organizativos exponen sistemáticamente la distancia entre las percepciones de madurez de la dirección y la realidad operativa, generando líneas de base más precisas y planes de desarrollo más útiles que las evaluaciones descendentes realizadas en solitario.

Las dos empresas involucradas en este estudio comprobaron que el progreso en DGL fue más rápido en las áreas operativas donde las disciplinas Lean ya estaban bien asentadas. Ello refuerza la lógica de secuenciación del modelo de madurez: la base Lean no es un requisito previo que deba completarse antes de que el DGL comience, pero la solidez de esa base en cada área determina directamente la velocidad a la que las capacidades I4.0 y EC pueden desarrollarse sobre ella.

8.3.3 Responsables políticos y reguladores

La evidencia comparativa de los dos casos ofrece varias observaciones relevantes para el diseño de políticas públicas. En primer lugar, la claridad y la estabilidad regulatoria importan más que la intensidad regulatoria para impulsar un desarrollo profundo de capacidades organizativas. La empresa europea no se benefició de la exigencia de los requisitos, sino de su previsibilidad y coherencia a lo largo de horizontes de planificación lo suficientemente largos como para permitir la inversión estratégica, en lugar de la mera minimización del incumplimiento. Los plazos que permiten un desarrollo genuino de capacidades, los mecanismos de apoyo a la transición y los marcos que generan ventaja competitiva para los primeros adoptantes, en vez de limitarse a penalizar a los rezagados, emergen como las palancas más eficaces para la transformación a largo plazo.

En segundo lugar, cuando las organizaciones participaron activamente en los procesos de elaboración regulatoria aportando conocimiento especializado, contribuyendo a diseñar marcos de implementación y ayudando a definir qué significa el cumplimiento en la práctica, desarrollaron capacidades más sofisticadas y lo hicieron con mayor rapidez que cuando esperaron a tener los requisitos definitivos para actuar. Los procesos regulatorios que crean canales significativos de participación para los profesionales del sector generan simultáneamente mejores regulaciones y organizaciones mejor preparadas, reforzando el valor de la coproducción entre reguladores y expertos del sector.

Por último, la brecha de infraestructura de conocimiento entre contextos institucionales es considerable y merece atención específica. Las organizaciones europeas se beneficiaron de ecosistemas densos de consultores, programas de investigación, redes entre pares y estándares sectoriales que las organizaciones de Oriente Medio tuvieron que suplir parcialmente a través de alianzas internacionales y desarrollo interno. Las políticas que invierten en infraestructura de conocimiento (como programas de investigación, apoyo a asociaciones sectoriales, desarrollo de la fuerza laboral, plantas piloto) generan beneficios que la presión regulatoria por sí sola no puede producir.

8.3.4 Consultores y proveedores de tecnología

El hallazgo más consistente en ambas empresas en relación con el apoyo externo fue que los colaboradores más valiosos eran quienes se involucraban con el contexto organizativo específico en lugar de aplicar marcos genéricos, quienes construían capacidad en el cliente en

lugar de crear dependencia, y quienes eran honestos sobre lo que sus soluciones podían y no podían ofrecer. Esto es más fácil de enunciar como principio que de adoptar como modelo de negocio; sin embargo, la evidencia empírica es inequívoca: las implementaciones que depositaron capacidad a largo plazo en las organizaciones cliente superaron, tanto en longevidad como en resultados, a aquellas que requerían una gestión externa continuada.

Para los proveedores de tecnología I4.0 en concreto, la información que proporciona el modelo de madurez sobre la secuenciación tiene implicaciones prácticas directas. Vender soluciones digitales en áreas organizativas donde las bases Lean son débiles, donde los procesos son inestables y hay falta de disciplina para la resolución de problemas, genera datos sin conocimiento e inversión sin retorno. La oportunidad comercial más duradera reside en ayudar a las organizaciones a evaluar su grado de preparación DGL antes del despliegue tecnológico, y en diseñar implementaciones que se apoyen en la estabilidad de los procesos, en lugar de intentar compensar su ausencia.

8.4 LIMITACIONES

8.4.1 Consideraciones metodológicas

Cada uno de los tres estudios empíricos empleó un método principal que conlleva limitaciones inherentes. La revisión sistemática de la literatura del Estudio 1 depende del conocimiento publicado y puede subestimar las perspectivas de los profesionales y las implementaciones fallidas que no lograron publicación académica. El modelo de madurez del Estudio 2 se construyó mediante lógica conceptual y validación de expertos, sin someter su estructura interna y sus relaciones de rendimiento a pruebas empíricas a gran escala. Los estudios de caso comparativos del Estudio 3 examinaron dos organizaciones, lo que aporta la profundidad necesaria para una comprensión contextual rica, pero limita la posibilidad de generalización estadística.

El diseño multimodal empleado en los tres estudios proporciona una triangulación que compensa parcialmente estas limitaciones individuales. Los resultados deben leerse como proposiciones teóricamente informadas y empíricamente fundamentadas, no como conclusiones definitivas derivadas de una investigación cuantitativa con muestras amplias. Ese es el desarrollo epistemológico adecuado para la investigación de fenómenos de naturaleza

emergente y profundamente dependientes del contexto, donde la elaboración teórica y la identificación de mecanismos tienen prioridad sobre la inferencia estadística.

8.4.2 Límites contextuales

La investigación se centró deliberadamente en la fabricación continua, esto es, en industrias de proceso continuo, concretamente la producción de aluminio en grandes corporaciones multinacionales que operan en contextos institucionales europeos y de Oriente Medio. Cada una de estas decisiones obedeció a una motivación analítica precisa: las industrias de fabricación continua presentan características que hacen que el Lean, la I4.0 y la EC se manifiesten de formas singulares; las grandes multinacionales disponen de la complejidad organizativa y los recursos que hacen visible el reto de integración en toda su envergadura; y el contraste entre los contextos europeo y de Oriente Medio proporciona la variación institucional que ilustra de qué manera el contexto configura los itinerarios de desarrollo de capacidades.

Estas mismas decisiones delimitan el alcance de la generalización con una base sólida. La fabricación discreta, los servicios y otras industrias de fabricación continua pueden exhibir dinámicas de integración distintas. Las pymes se enfrentan a restricciones de recursos y capacidades que hacen poco realistas los niveles superiores del modelo de madurez sin apoyo externo, y pueden requerir marcos sustancialmente diferentes. Los contextos institucionales asiáticos, norteamericanos, latinoamericanos y africanos revelarían con toda probabilidad variaciones adicionales en los itinerarios que no quedan recogidas en este estudio. Los marcos conceptuales empleados —la identificación de tensiones de integración, las categorías de capacidades y los mecanismos de influencia institucional— son, con toda seguridad, más transferibles más allá de estas fronteras que los detalles específicos de implementación y las descripciones de cada nivel de madurez.

8.4.3 Restricciones en la recogida de datos

La investigación mediante estudio de casos depende de las posibilidades de acceso a la organización y de la disposición de los participantes. Ambas empresas proporcionaron un acceso sustancial, aunque algunas restricciones resultaron inevitables: la información comercialmente sensible no fue compartida; la participación se concentró en niveles directivos, con perspectivas limitadas de los trabajadores de primera línea; y el carácter retrospectivo de los relatos obtenidos mediante entrevistas implica que los participantes

reconstruyeron la historia de su organización con mayor coherencia narrativa de la que probablemente tuvo la experiencia en tiempo real. La recogida de datos dentro de cada caso ofrece una triangulación que reduce estos efectos, aunque no los elimina por completo. Los hallazgos representan las perspectivas de los participantes sobre el desarrollo del DGL, perspectivas que pueden diferir de las de otros grupos de interés organizativos o de observadores con distintos enfoques analíticos.

8.4.4 Decisiones analíticas

Este trabajo empleó tres perspectivas teóricas: capacidades dinámicas (Teece, 2007), teoría institucional (DiMaggio & Powell, 1983) y teoría de la paradoja (Smith & Lewis, 2011). Se seleccionaron porque, en conjunto, abordan las tres preguntas centrales que la investigación plantea: cómo las organizaciones construyen capacidades DGL integradas, cómo los contextos institucionales configuran esos itinerarios de desarrollo, y cómo las organizaciones navegan las tensiones estructurales que genera la integración. Cada perspectiva destaca ciertos fenómenos y deja otros en segundo plano; esa selección es, a la vez, una fortaleza y una limitación que conviene reconocer con claridad.

La visión basada en recursos, RBV, por sus siglas en inglés, (Barney, 1991) fue inicialmente la alternativa más evidente para la dimensión de capacidades. Habría enmarcado las capacidades DGL como fuentes de ventaja competitiva sostenida y habría dirigido la atención analítica hacia las condiciones de rareza, inimitabilidad y no sustituibilidad. Este enfoque se consideró y se descartó porque la pregunta de investigación no es qué organizaciones obtienen ventaja competitiva a través del DGL, sino cómo desarrollan esas capacidades a lo largo del tiempo. El enfoque de las capacidades dinámicas, con su énfasis en la detección de oportunidades, su aprovechamiento y la reconfiguración en respuesta a entornos cambiantes (Teece, 2007), encaja mejor con esa pregunta.

Para la dimensión institucional, la teoría de sistemas sociotécnicos (Geels, 2011) ofreció un marco alternativo que fue considerado, en particular para analizar cómo la I4.0 y la EC desestabilizan y reconfiguran los regímenes de fabricación existentes. Su fortaleza reside precisamente en el análisis de las transiciones a nivel de régimen; su limitación para esta tesis es que opera principalmente a nivel sistémico y proporciona escasa comprensión de los procesos de desarrollo de capacidades a nivel organizativo, que era exactamente lo que el estudio de casos estaba diseñado para examinar. La teoría institucional, con su enfoque en

cómo los marcos regulatorios, las presiones de legitimidad y los ecosistemas de conocimiento moldean la práctica organizativa, encajó de forma más directa con el diseño de la investigación y el estudio empírico.

La teoría de la complejidad fue considerada como marco alternativo para las tensiones de integración presentes en los tres estudios. Habría caracterizado las tensiones eficiencia-circularidad y estandarización-digitalización como propiedades emergentes de sistemas adaptativos complejos, en lugar de paradojas estructurales que requieren capacidad de gestión (Anderson, 1999; Stacey, 1995). Ese enfoque resultó finalmente menos útil para los profesionales, porque explica la persistencia de la tensión sin generar orientación aplicable para los líderes que deben decidir cómo responder en la práctica. La atención explícita de la teoría de la paradoja a las prácticas de liderazgo y las rutinas organizativas para trabajar productivamente con objetivos y necesidades que compiten entre sí, en lugar de resolverlas artificialmente, conecta de forma más directa con las implicaciones prácticas que la investigación pretende generar.

El marco DGL que resulta de estas decisiones debe entenderse, por tanto, como una construcción conceptual teóricamente informada que refleja las prioridades del diseño de investigación y las preguntas que este plantea, no como un marco que sería idéntico bajo diferentes supuestos teóricos. Perspectivas alternativas habrían producido comprensiones distintas, quizá igualmente válidas, a partir del mismo material empírico.

8.4.5 La posición del investigador

Más de veinticinco años de experiencia en la industria manufacturera proporcionan ventajas reales para una investigación de estas características: credibilidad ante los participantes, capacidad para reconocer y explorar detalles operativos significativos, y conocimiento de primera mano de lo que suponen los retos directivos descritos para quien los afronta desde dentro de una organización que los vive. Pero esta misma trayectoria genera riesgos que es necesario reconocer: posibles sesgos sobre cuáles son los retos que más importan, cierta tendencia a dar mayor peso a las perspectivas de la alta dirección que coinciden con la experiencia profesional previa, y potenciales puntos ciegos sobre las limitaciones del Lean en contextos donde su lógica no se traslada de forma directa.

Distintas prácticas de reflexión como el reconocimiento explícito del bagaje del investigador, los protocolos sistemáticos de recogida y codificación de datos, la presentación transparente

de los datos, la verificación con los participantes y la supervisión académica continuada, mitigan parcialmente estos riesgos. Investigadores con trayectorias distintas identificarían con toda probabilidad patrones diferentes en el mismo material empírico, y esa diversidad de perspectivas forma parte del avance del campo. Esta investigación representa la visión de un profesional-investigador, con las fortalezas y las limitaciones que esa combinación necesariamente conlleva.

8.4.6 Alcance temporal

La investigación recoge la transformación DGL en un momento histórico específico —de 2020 a 2025—, cuando la I4.0 y la EC seguían siendo emergentes en la mayoría de las organizaciones manufactureras y los marcos de gestión para abordarlas todavía se estaban desarrollando. Las capacidades tecnológicas evolucionarán, los marcos regulatorios madurarán y los retos específicos de integración documentados en este estudio pueden cambiar de naturaleza a medida que las organizaciones acumulen experiencia. El diseño transversal implica además que las trayectorias de desarrollo organizativo se infieren a partir de la observación en un momento puntual, en lugar de seguirse longitudinalmente, lo que limita la comprensión de cómo se sostienen las capacidades a lo largo del tiempo y qué factores determinan si el progreso inicial en DGL se consolida o se estanca.

8.4.7 Niveles de confianza

Estas limitaciones apuntan hacia una confianza diferenciada según los aspectos de los hallazgos que se consideren. La identificación conceptual de los impactos de la I4.0 y la EC sobre la Cultura y el Liderazgo Lean, la caracterización de las cuatro tensiones fundamentales de integración, y el hallazgo de que el contexto institucional configura los itinerarios de desarrollo de capacidades se apoyan en evidencia convergente procedente de múltiples métodos y de ambos contextos empíricos, lo que les otorga un nivel de confianza relativamente elevado. Las definiciones específicas de los niveles de madurez, los recuentos precisos de capacidades (19 competencias, 10 características y 81 capacidades de madurez) y los mecanismos concretos observados en las dos empresas del estudio requieren validación empírica adicional antes de proceder a su generalización. Las afirmaciones sobre la aplicabilidad a las pymes, a contextos más allá de la fabricación continua y sobre la sostenibilidad de las capacidades a largo plazo son las más especulativas y exigen la

interpretación más cautelosa, lo que indica que el nivel de confianza varía de forma sistemática entre las dimensiones conceptual, empírica y predictiva de la investigación.

8.5 LÍNEAS DE INVESTIGACIÓN FUTURA

8.5.1 Desarrollo teórico

El modelo de madurez desarrollado en el Estudio 2 se construyó mediante lógica conceptual y validación experta. La prioridad investigadora más urgente es desarrollar instrumentos de medición validados para las 81 capacidades identificadas. Los procedimientos estándar de desarrollo de escalas, tales como generación de ítems, revisión por expertos, pruebas piloto y análisis factorial confirmatorio, permitirían contrastar el modelo en contextos de fabricación diversos y examinar cuantitativamente su relación con los resultados de rendimiento operativo. Este proceso también revelaría si la estructura de siete dimensiones se mantiene en distintos sectores, si la progresión de cinco niveles refleja realmente las secuencias de desarrollo observadas en la práctica, y si las organizaciones con niveles de madurez más elevados alcanzan resultados DGL demostrablemente superiores.

8.5.2 Estudios de proceso longitudinales

La investigación transversal puede identificar cómo son las capacidades organizativas en un momento dado, pero no puede observar directamente cómo se desarrollan a lo largo del tiempo. Los estudios longitudinales que sigan a organizaciones manufactureras a través de su transformación DGL mediante observación en tiempo real, entrevistas repetidas y documentación de incidentes críticos durante periodos de tres a cinco años, revelarían dinámicas de desarrollo que la investigación puntual no puede capturar: cómo condicionan las brechas específicas de capacidad el desarrollo posterior, qué desencadena las transiciones entre niveles de madurez, qué inversiones tempranas en capacidades resultan más determinantes para el progreso DGL a largo plazo. Estas preguntas requieren diseños prospectivos longitudinales para ser respondidas con fiabilidad y para permitir a los investigadores observar los mecanismos de dependencia de trayectoria, los efectos de secuenciación y el refuerzo mutuo de capacidades que permanecen invisibles en los diseños estáticos.

8.5.3 Expansión contextual

Distintos entornos contextuales abordarían los límites identificados en la Sección 8.4.2 y permitirían evaluar la estabilidad del marco DGL bajo configuraciones institucionales y culturales marcadamente distintas. Contextos de fabricación discreta como el ensamblaje de automoción, la electrónica, la industria aeroespacial o el sector de la defensa, permitirían comprobar si las tensiones de integración y las categorías de capacidad identificadas aquí se transfieren o requieren modificación cuando no están presentes las características propias del proceso continuo. La investigación en pymes examinaría si los niveles superiores del modelo de madurez son alcanzables sin los recursos de una gran organización y qué mecanismos externos de apoyo sustituyen con mayor eficacia a la capacidad interna. La expansión geográfica hacia contextos manufactureros asiáticos sería especialmente valiosa, habida cuenta del liderazgo simultáneo de esas regiones en la adopción de I4.0, su creciente ambición política en materia de EC y sus tradiciones Lean profundamente arraigadas, pero culturalmente distintas de los contextos europeo y de Oriente Medio analizados en este estudio.

8.5.4 La gestión de paradojas como capacidad organizativa

El hallazgo de que las cuatro tensiones de integración requieren gestión productiva antes que resolución técnica tiene implicaciones que esta tesis ha identificado sin haberlas explorado en toda su profundidad. ¿Qué prácticas específicas de liderazgo posibilitan una gestión productiva de las tensiones en contextos DGL? ¿Cómo se desarrolla esa capacidad de gestión a lo largo del tiempo organizativo? ¿Se construye a través de la formación, de la experiencia acumulada en episodios concretos de tensión, o mediante mecanismos estructurales que generan una exposición repetida a demandas en competencia? ¿Qué condiciones hacen que las mismas tensiones generen respuestas organizativas creativas en unos contextos y parálisis o conflicto destructivo en otros? Estas preguntas se abordan mejor mediante estudios de caso longitudinales con observación en tiempo real de cómo responden las organizaciones a episodios específicos de retos de integración.

8.5.5 Investigación de integración específica por tecnología

Esta tesis examinó la I4.0 como un conjunto de tecnologías cuyas implicaciones organizativas se analizaron a nivel general. A medida que tecnologías específicas van madurando y la experiencia de implementación se acumula, la investigación más detallada de los retos de

integración se revela posible y valiosa. ¿De qué manera interactúa el despliegue de la optimización de procesos basada en inteligencia artificial con el énfasis del Lean en la capacidad de resolución de problemas por parte del operario? ¿Qué ocurre con las disciplinas del gemba cuando los gemelos digitales ofrecen una simulación completa del proceso? ¿Cómo alteran los robots móviles autónomos los patrones de colaboración humano-máquina de los que dependen las culturas Lean? Estas preguntas específicas de cada tecnología requieren diseños de investigación que examinen la implementación con suficiente profundidad operativa como para observar las dinámicas culturales y de liderazgo que la investigación I4.0 de nivel general no puede alcanzar.

En un plano más amplio, la emergente agenda de la Industria 5.0, con su énfasis en una fabricación centrada en las personas, resiliente y sostenible (European Commission, 2021), ofrece un marco conceptual y de política natural en el que situar la investigación futura sobre DGL, extendiendo la relevancia del marco más allá del enfoque tecnológico de la I4.0 hacia los retos organizativos y sociales más amplios que exigirá la próxima transición industrial.

8.6 REFLEXIONES FINALES

Esta tesis partió de una observación práctica: las organizaciones manufactureras de todo el mundo afrontan requisitos de transformación simultáneos en excelencia operativa, capacidad digital y economía circular, mientras que la literatura no había proporcionado marcos adecuados para navegarlos de forma conjunta. Lo que esta investigación ha puesto en evidencia es que la integración no es meramente aditiva, que las tensiones entre los tres paradigmas son estructurales y no casuales, y que el liderazgo y la cultura son las dimensiones organizativas en las que la integración o prospera o fracasa.

El marco DGL desarrollado en esta investigación es un comienzo, no una conclusión. Los cinco niveles del modelo de madurez describen una progresión de desarrollo que las organizaciones reales recorren de maneras más complejas, más contradictorias y ricas de lo que cualquier modelo puede capturar. Las categorías de capacidades derivadas de los estudios reflejan dos contextos institucionales específicos y requerirán adaptación a medida que la investigación se extienda a otras industrias y geografías. Las tensiones de integración identificadas en los tres estudios evolucionarán previsiblemente de carácter a medida que las tecnologías I4.0

maduren, los marcos regulatorios de la EC se consoliden y las organizaciones acumulen mayor experiencia con los compromisos concretos que esas tensiones exigen.

Nada de todo esto debilita lo que esta investigación establece. Las organizaciones pueden integrar excelencia operativa, digitalización y circularidad: las dos empresas del estudio así lo demuestran, de forma imperfecta e incompleta, pero genuina y sostenida en el tiempo. La integración requiere capacidades organizativas que son identificables, evaluables y desarrollables mediante una atención estructurada a lo largo del tiempo. El contexto institucional moldea significativamente los itinerarios, pero no determina los resultados: las organizaciones que se relacionan activamente con sus entornos institucionales en lugar de simplemente adaptarse desarrollan de forma sistemática capacidades DGL más completas que aquellas que responden de manera reactiva y pasiva.

Las cuatro tensiones de integración identificadas, eficiencia frente a circularidad, estandarización frente a digitalización, cumplimiento normativo frente a ventaja competitiva, y rendimiento a corto plazo frente a capacidad a largo plazo, no desaparecerán en los niveles de madurez más elevados. Son rasgos propios del área organizativo, no defectos de la implementación. Aprender a navegar estas tensiones de forma productiva, a sostener demandas en competencia sin resolverlas artificialmente, a mantener la ambigüedad sin caer en la parálisis es, en sí misma, la competencia de liderazgo fundamental que el DGL exige. Y no es casualidad que sea también lo que hacen los líderes de las organizaciones más eficaces que he tenido la oportunidad de conocer a lo largo de más de veinticinco años en la industria: no quienes tienen más respuestas, sino quienes saben sostenerse con mayor serenidad en las preguntas difíciles.

Para los investigadores, los marcos propuestos en este estudio están concebidos como herramientas para la investigación posterior, no como conclusiones que confirmar. El contraste riguroso, la implicación crítica, la extensión contextual y el rechazo en favor de alternativas mejores son todas ellas formas legítimas de avance de la disciplina, y todas son bienvenidas. Para los profesionales, los marcos son puntos de partida para el diagnóstico organizativo y la planificación del desarrollo. Cada organización que navegue la transformación DGL habrá de encontrar su propio camino, a través de las condiciones institucionales específicas, la historia operativa, las capacidades de liderazgo y los puntos de partida culturales que le son propios.

Las organizaciones manufactureras que logren integrar con éxito la excelencia operativa, la I4.0 y la EC dispondrán de ventajas competitivas significativas en las próximas décadas. Más importante aún: habrán demostrado que la producción industrial y la circularidad no son objetivos opuestos que requieran compromisos permanentes, sino dimensiones complementarias de la capacidad organizativa que se refuerzan mutuamente cuando se persiguen con suficiente inteligencia, disciplina y compromiso sostenido. Esa demostración importa mucho más allá de la posición competitiva de cualquier organización individual: importa para el conjunto de las organizaciones manufactureras y para los debates más amplios sobre cómo la industria puede ser, simultáneamente, excelente y sostenible. Esta investigación se ofrece como una contribución modesta pero útil para hacer más probable que esa demostración llegue a producirse, y para que las investigaciones futuras y la práctica directiva puedan refinar, cuestionar y ampliar los fundamentos aquí establecidos.

NOTA: BIBLIOGRAFÍA DE ESTE CAPÍTULO

La bibliografía consolidada de todas las referencias citadas en los Capítulos 1, 2, 3, 7 y 8 se incluye en el Anexo A. Los Capítulos 4, 5 y 6 son artículos publicados o en proceso de publicación y, por tanto, mantienen sus referencias bibliográficas originales, tal como fueron publicadas o enviadas.

ANNEX A: BIBLIOGRAPHY

Note: This bibliography consolidates all references cited in Chapters 1, 2, 3, 7, and 8 of this thesis. Chapters 4, 5, and 6 are published or submitted papers and retain their original bibliographies as published/submitted.

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ANNEX B: INTERVIEW GUIDE

DIGITAL GREEN LEAN FRAMEWORK

Semi-Structured Interview Guide

Study 3 -- Comparative Case Studies in Aluminum Manufacturing

Researcher	Ignacio Sanchez Gatell
Institution	Universidad de Oviedo
Supervisor	Prof. Lucia Avella Camarero
Interview version	v1.0 -- January 2024
Estimated duration	60-90 minutes
Analytical framework	Gioia Methodology (Gioia et al., 2013; Magnani & Gioia, 2023)
Regions covered	Europe (EU) and Middle East (ME) -- multinational aluminum producers

Purpose of this Guide

This interview guide supports Study 3 of the Digital Green Lean (DGL) doctoral thesis. It explores how organizations in different regional institutional contexts develop capabilities for Circular Economy (CE) implementation within established Lean Manufacturing systems. Questions are grounded in the DGL Maturity Assessment Model (Study 2) and structured around the four aggregate capability dimensions identified through Gioia analysis.

Research Question RQ3: How do regional institutional contexts influence organizational capability development for Digital Green Lean, and what mechanisms enable this while maintaining operational excellence? (Focused on CE)

INTERVIEWER INSTRUCTIONS

Before the interview:

- * Confirm consent and record permission. Remind participant that company and personal identity will be anonymized (EU1-EU6, ME1-ME5).
- * Review the participant's functional role and confirm regional context before starting.
- * This guide is semi-structured. Follow the participant's narrative; do not read questions mechanically.

Gioia methodology principles:

- * Preserve informant language. Use the participant's own terms; do not impose framework categories.
- * Allow silences. Long pauses often precede the richest responses.
- * Note verbatim expressions that participants use repeatedly -- these become first-order codes in MaxQDA.

Mapping to maturity model dimensions:

- * Each subsection is mapped to the relevant DGL Maturity Assessment dimensions (Culture and Leadership sheets). This mapping guides interpretation but should not be made visible to participants.

SECTION A -- PARTICIPANT CONTEXT & WARM-UP

Purpose: Establish rapport, confirm role context, and surface the participant's own language for sustainability and operational priorities before entering structured topics.

Q1	Could you briefly describe your current role and how long you have been with the company? -> What does your day-to-day work look like in relation to operational or sustainability initiatives?
Q2	How would you describe the company's overall manufacturing philosophy? What principles guide the way operations are run here? -> When did Lean Manufacturing become a significant part of the way this organization works?

Q3	Over the past few years, how has the topic of sustainability or circular economy entered your operational conversations? Did it arrive from leadership, from regulatory requirements, or from somewhere else? <i>-> How did people in your team first react to it?</i>
NOTE	<i>Record the words participants use naturally for sustainability, circularity, and digital tools -- these are first-order code candidates.</i>

SECTION B -- STRATEGIC VISION & COMMITMENT

Aggregate Dimension 1 of Study 3: Strategic Vision & Commitment. Covers how organizational leadership sets long-term direction, resources sustainability initiatives, and aligns Lean and CE goals.

B1	Leadership Vision and CE Strategic Direction <i>-> Maturity model mapping: DGL Leadership: Performance Driven (Target setting, Targets deployment) DGL Culture: Customer Centric (Performance orientation)</i>
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Q4	How does your organization's senior leadership communicate its long-term commitment to circular economy practices? Can you give a concrete example of that? <i>-> Is this framed primarily as a compliance requirement, a cost-reduction opportunity, or a strategic priority -- and does that framing differ between leadership levels?</i>
Q5	When circular economy goals are set, how are they integrated into the operational targets that plant or production managers are held accountable for? <i>-> Has Hoshin Kanri or any similar strategy deployment method been used to cascade CE goals to the shopfloor?</i>
Q6	In your experience, what happens when sustainability targets and production efficiency targets come into tension? Who resolves that, and how?

	-> Can you recall a specific situation where that tension came to a head?
NOTE	Probe for the presence -- or absence -- of formal mechanisms linking CE strategy to operational KPIs. Note whether EU and ME contexts use different language: "compliance" vs. "national vision" vs. "competitive advantage".

B2	Resource Allocation and Organizational Commitment -> Maturity model mapping: DGL Leadership: Personal Development (Empowerment, Self-transcendence) DGL Culture: Values & Principles (Authority distribution)
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Q7	What level of organizational investment -- in terms of people, budget, and time -- has the company made specifically for CE capability development? How was that decision made? -> Is that investment treated as a capital project or as an ongoing operational cost?
Q8	Are there dedicated roles or teams responsible for driving CE implementation? How are they positioned in relation to the Lean or operational excellence functions? -> Do CE and Lean specialists typically work together, or do they operate in parallel?
NOTE	Observe whether investment decisions are described as top-down mandates or as responses to external pressure (regulatory, customer, investor). This distinction is analytically important for the EU/ME comparison.

SECTION C -- OPERATIONAL INTEGRATION MECHANISMS

Aggregate Dimension 2 of Study 3: Operational Integration Mechanisms. Covers the process redesign, technology adoption, and organizational structures through which CE practices are embedded into Lean production operations.

C1	Lean-CE Integration in Process Design -> Maturity model mapping: DGL Leadership: Lean Principles (Process & lean expertise, Genchi genbutsu, Experimental) DGL Culture: Operational Excellence (Problem solving, CI & Innovation)
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Q9	How have your production processes been redesigned to accommodate circularity -- for example, material recovery, recycling loops, or waste reuse -- without compromising the flow and efficiency principles you already have in place? -> Did those redesigns feel like an extension of Lean logic or did they require a fundamentally different approach?
Q10	Can you walk me through a specific process improvement or innovation where Lean problem-solving methods were used to address a circularity challenge? -> What tools were used -- A3, Value Stream Mapping, PDCA -- and were they adapted in any way for the CE context?
Q11	Where in your operations have you found it most difficult to make Lean and CE principles work together? What made it difficult? -> Is the tension between efficiency and regeneration something you have an explicit language for in your organization?
NOTE	Look for evidence that Lean serves as an enabling platform for CE (as the thesis argues) versus cases where informants describe Lean as a constraint on circular transformation.

C2	Digital Technology as CE Enabler -> Maturity model mapping: DGL Leadership: Lean Principles (Process & lean expertise, Experimental) DGL Culture: Customer Centric (Performance orientation -- Data storage & analysis)
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Q12	How are digital tools -- IoT sensors, analytics platforms, digital twins, or AI -- being used in your facility to support circular practices such as tracking material flows, monitoring energy consumption, or optimizing recycled input quality?
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	<i>-> Were these technology investments driven by CE goals specifically, or were they part of broader Industry 4.0 initiatives that later found CE applications?</i>
Q13	Has the availability of real-time operational data changed the way your team makes decisions about waste reduction or resource efficiency? <i>-> Can you give a concrete example of a decision that was made differently because of better data availability?</i>
Q14	What has been the biggest challenge in integrating digital systems with existing Lean processes? How did you -- or your team -- handle that? <i>-> Was it primarily a technical challenge, a human factor, or an organizational design issue?</i>
NOTE	<i>Capture specific digital tool names as informant first-order codes. The distinction between "digital for efficiency" and "digital for circularity" is analytically important for the theoretical contribution.</i>

C3	Organizational Design for DGL Integration <i>-> Maturity model mapping: DGL Leadership: Customer Oriented (Teamworking) DGL Culture: Values & Principles (Power distance, Organizational Design)</i>
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Q15	How is your organization structured to coordinate between sustainability, digital transformation, and Lean operational excellence? Are these functions integrated, or do they operate in separate silos? <i>-> How does that structure affect the speed at which CE initiatives are translated into operational practice?</i>
Q16	Has the introduction of automation -- robots, cobots, or autonomous systems -- changed how teams are organized on the shopfloor? How do people relate to those technologies in practice? <i>-> Has that changed anything about the leadership or supervisory model at the operational level?</i>

NOTE	<i>Power distance differences between EU and ME contexts may surface in answers about organizational hierarchy, decision-making authority, and the degree of autonomy given to operational teams.</i>
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SECTION D -- STAKEHOLDER ENGAGEMENT SYSTEMS

Aggregate Dimension 3 of Study 3: Stakeholder Engagement Systems. Covers how organizations engage internal and external stakeholders -- employees, customers, suppliers, regulators -- in CE capability development.

D1	Internal Mobilization and Employee Engagement <i>-> Maturity model mapping: DGL Leadership: Customer Oriented (Teamworking) DGL Culture: Values & Principles (Collectivism, Human orientation) Operational Excellence (Receptiveness)</i>
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Q17	How do employees at the shopfloor level engage with circular economy initiatives? Is it something they are actively involved in designing, or primarily something they are asked to implement? <i>-> How does that compare to the level of employee involvement you have in typical Lean continuous improvement activities?</i>
Q18	How does your organization manage the cultural shift required for employees to move from a "produce more efficiently" mindset to a "produce and recovery" or "close the loop" mindset? <i>-> Have there been specific training programs, communication campaigns, or behavioral change initiatives aimed at this?</i>
Q19	Are there mechanisms for employees to propose CE improvements - similar to kaizen events or suggestion systems in Lean? How do those work in practice? <i>-> What percentage of CE improvement ideas, roughly, originate from operations versus from management or engineering?</i>
NOTE	<i>Responses here may reveal important EU/ME differences: regulatory culture versus national vision culture in how CE is framed to employees (obligation vs. pride vs. competitive advantage).</i>

D2	External Stakeholders: Customers, Suppliers and Regulators -> Maturity model mapping: DGL Leadership: Customer Oriented (Customer focus, Customer & supplier development) DGL Culture: Customer Centric (Sustainable Customer Orientation)
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Q20	How does your organization work with suppliers to integrate circular economy principles into the supply chain -- for example, take-back schemes, recycled input sourcing, or shared material tracking? -> Has Lean supplier development methodology been extended to cover CE requirements? If so, how?
Q21	To what extent do your customers drive circular economy requirements? Are CE specifications or commitments part of customer contracts or SLAs? -> Has customer demand for circular products or services changed over the past three to five years?
Q22	How does the regulatory or policy environment in your region shape the pace and direction of your CE implementation? Do you see regulation primarily as a driver, a constraint, or both? -> Has a specific policy or regulation been the trigger for a major CE initiative here?
NOTE	The contrast in regulatory framing between Europe (compliance-driven) and Middle East (vision-led) is central to RQ3. Capture exact language participants use to describe external pressures.

SECTION E -- LEARNING & ADAPTATION PROCESSES

Aggregate Dimension 4 of Study 3: Learning & Adaptation Processes. Covers how organizations build knowledge, develop leadership and workforce capabilities, and adapt over time to sustain CE progress.

E1	Knowledge Acquisition and Capability Building -> Maturity model mapping: DGL Leadership: Personal Development (Self-developing, Human-centric, Development & coaching) DGL Culture: Operational Excellence (CI & Innovation)
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Q23	What have been the most effective ways in which your organization has built the technical and managerial capabilities needed for CE implementation? Formal training, learning by doing, external partnerships, or something else? <i>-> Has the development of CE capabilities followed a similar path to how Lean capabilities were built when the company first adopted Lean?</i>
Q24	How does your organization capture and transfer learning from CE pilots or experiments to other plants or operating units? <i>-> Are there specific systems -- communities of practice, lessons-learned databases, cross-site review meetings -- dedicated to this?</i>
Q25	Which leadership behaviors have been most important in enabling the organization to learn and adapt in the CE transition? Can you describe a leader who has been particularly effective in this area, and what they did differently? <i>-> Has the company explicitly revised its leadership competency framework to include sustainability or CE capabilities?</i>
NOTE	<i>Responses about leadership behaviors may generate rich first-order codes aligned with the DGL Leadership maturity model. Note servant leadership, self-transcendence, and empowerment language specifically.</i>

E2	Problem-Solving Culture and Experimentation <i>-> Maturity model mapping: DGL Leadership: Lean Principles (Experimental, Zero-defects, Problem-solving, Genchi genbutsu) DGL Culture: Operational Excellence (Problem solving culture -- scientific method)</i>
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Q26	How does your organization approach the uncertainty involved in CE innovation -- for example, testing a new recycling process or a new material substitution -- given that Lean typically favors stable, controlled processes? <i>-> Is experimentation culturally accepted here, or does it create discomfort?</i>
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Q27	Can you describe a CE improvement initiative that did not work as planned? What did the organization learn from it, and how was that learning handled? <i>-> Was the response different from how the company typically handles a quality failure or a Lean implementation setback?</i>
Q28	To what extent is shopfloor observation -- going to the gemba -- part of how CE problems are diagnosed and solved? Has the scope of what leaders are expected to observe expanded to include sustainability dimensions? <i>-> What does a "CE gemba walk" look like in practice in your facility?</i>
NOTE	<i>Kata-style experimentation and PDCA cycles applied to CE problems are key indicators of how the maturity model "Experimental" subdimension manifests in practice.</i>

SECTION F -- INSTITUTIONAL CONTEXT AND REGIONAL COMPARISON

Purpose: Surface the participant's own interpretation of how the institutional context -- regulatory, cultural, national -- shapes the organization's CE journey. Particularly important for the EU/ME comparative analysis.

Q29	If you compare your CE journey here with what you know of similar operations in other regions, what do you see as the most significant differences in terms of pace, approach, or priorities? <i>-> Is there anything about the local or national context here that has made CE implementation easier -- or harder -- than it might be elsewhere?</i>
Q30	In your view, is the primary motivation for CE implementation here driven by external requirements -- regulations, customer demands, investor pressure -- or by an internal conviction that this is the right direction for the business? <i>-> Has that balance shifted over the time you have been working on this?</i>
Q31	How does the national culture or institutional environment here affect the way employees, managers, and leaders engage with CE and sustainability goals?

	<i>-> Are there specific cultural values or norms -- around hierarchy, collective action, or innovation -- that you feel are particularly relevant to how CE is being adopted?</i>
Q32	Looking three to five years ahead, what do you see as the most significant capability gaps your organization still needs to close to be genuinely operating as a circular manufacturing business? <i>-> What will need to change -- in leadership, in culture, in processes, or in technology -- to close those gaps?</i>
NOTE	<i>This section is key for distinguishing the "regulatory-driven sequential pathway" (Europe) from the "leadership-driven experimental pathway" (Gulf/Middle East) identified in Chapter 6.</i>

SECTION G -- CLOSING

Q33	Is there anything about your organization's Lean-CE integration experience that you feel is important but that we have not yet had the chance to discuss?
Q34	If you were advising another manufacturing leader starting this journey today, what would be the single most important thing you would tell them about developing circular economy capabilities within a Lean organization?
NOTE	<i>Thank the participant for their time. Confirm consent for follow-up contact if needed for member checking. Remind them of anonymization and expected publication timeline.</i>

APPENDIX -- MATURITY MODEL DIMENSION MAPPING REFERENCE

Section	Aggregate Dimension (Study 3)	DGL Culture Dimensions	DGL Leadership Dimensions
A	Context & Warm-up	All dimensions (orientation)	All dimensions (orientation)
B1-B2	Strategic Vision & Commitment	Customer Centric (Performance orientation); Values & Principles (Authority distribution)	Performance Driven (Target setting, Deployment); Personal Development (Empowerment, Self-transcendence)
C1-C3	Operational Integration Mechanisms	Operational Excellence (Problem solving, CI & Innovation); Customer Centric (Performance orientation)	Lean Principles (Process expertise, Experimental, Genchi genbutsu); Customer Oriented (Teamworking)
D1-D2	Stakeholder Engagement Systems	Values & Principles (Collectivism, Human orientation); Customer Centric (Sustainable Customer Orientation); Operational Excellence (Receptiveness)	Customer Oriented (Customer focus, Customer & supplier development)
E1-E2	Learning & Adaptation Processes	Operational Excellence (CI & Innovation, Problem solving culture)	Personal Development (Self-developing, Human-centric, Development); Lean Principles (Experimental, Zero-defects, Problem-solving)
F-G	Institutional Context & Closing	Values & Principles (all subdimensions)	All leadership dimensions (integrative)

Total: 34 open-ended questions | 7 sections | Mapped to all DGL Maturity Model dimensions (Culture + Leadership) | Designed for Gioia analysis in MaxQDA 2024

-----END OF THESIS-----