DOCTORAL THESIS

Systemic Sustainability and Agility as New Organizational Paradigms for Managing Complexity in Supply Chains

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RESUMEN

Esta tesis doctoral analiza la sostenibilidad sistémica, en combinación con la agilidad organizacional, como nuevo paradigma organizativo para gestionar la complejidad de las cadenas de suministro manufactureras en la transición desde la Industria 4.0 hacia la Industria 5.0 y su proyección futura hacia la Industria 6.0. En las últimas décadas, la Industria 4.0 ha impulsado la digitalización, automatización e interconexión de los sistemas productivos, pero los retos asociados a la crisis climática, la degradación de recursos naturales, las desigualdades sociales y la vulnerabilidad de las cadenas globales han puesto de manifiesto las limitaciones de modelos centrados casi exclusivamente en la eficiencia económico-financiera. En este contexto, la Industria 5.0 se formula como un paradigma emergente que sitúa en el centro la sostenibilidad, la resiliencia y la centralidad humana, mientras que la noción de sostenibilidad sistémica propone una visión holística en la que las dimensiones económica, ambiental, social y tecnológica se entienden como profundamente interconectadas y co-evolutivas. La agilidad organizacional se concibe, en este marco, como una capacidad dinámica clave para reconfigurar recursos, procesos y relaciones ante entornos volátiles sin desalinearse de los objetivos de sostenibilidad a largo plazo.

La tesis se presenta en modalidad de compendio de publicaciones, integrando tres artículos científicos ya publicados en revistas académicas internacionales de impacto. Cada artículo constituye un bloque de trabajo diferenciado, con objetivos y métodos propios, pero diseñado desde el inicio como parte de un programa de investigación coherente que aborda, desde ángulos complementarios, la misma cuestión central: cómo conceptualizar y operacionalizar la sostenibilidad sistémica en cadenas de suministro manufactureras complejas que deben seguir siendo ágiles. El hilo conductor entre los tres artículos es doble: por un lado, el desarrollo progresivo de marcos teórico-metodológicos que avanzan desde lo conceptual a lo operativo; por otro, la aplicación coherente de estos marcos al distrito cerámico italiano, un sector industrial intensivo en energía y recursos que actúa como caso empírico unificador.

La revisión de la literatura revela varios vacíos que dificultan la implementación real de estos planteamientos. En primer lugar, existe una brecha notable entre la sofisticación teórica de los enfoques de sostenibilidad sistémica y la disponibilidad de herramientas operativas que permitan a directivos y responsables de cadena de suministro utilizarlos en la toma de decisiones. En segundo lugar, la mayoría de los marcos de sostenibilidad adoptan una perspectiva implícitamente universalista y descontextualizada, prestando escasa atención al arraigo territorial de los sistemas productivos, cuando en realidad muchos sectores manufactureros se organizan en torno a distritos industriales con historias, culturas, instituciones y redes específicas. En tercer lugar, la dimensión social de la sostenibilidad sigue siendo la menos desarrollada: abundan enfoques basados en juicios cualitativos o listas de comprobación, pero escasean metodologías cuantitativas basadas en datos que permitan evaluar de forma sistemática y comparable los impactos sociales a nivel organizacional. En cuarto lugar, la integración entre termoeconomía y gestión empresarial ha sido limitada, pese al potencial del análisis exergético para proporcionar una base física rigurosa a la evaluación de la eficiencia y de los límites de los sistemas productivos. Finalmente, la relación entre sostenibilidad sistémica, agilidad organizacional y el emergente paradigma de Industria 5.0 se ha abordado de forma fragmentada, con escasez de marcos que las articulen simultáneamente de manera coherente y aplicable en cadenas de suministro complejas.

A partir de estos antecedentes, la tesis se estructura en torno a una pregunta de investigación global: cómo conceptualizar y analizar la sostenibilidad sistémica en sistemas manufactureros de modo que resulte operativa para la toma de decisiones en cadenas de suministro complejas que, además, deben mantener elevados niveles de agilidad. De esta cuestión amplia se derivan cuatro preguntas específicas que profundizan en dimensiones clave del problema. La primera se centra en cómo analizar la sostenibilidad sistémica en distritos industriales manufactureros incorporando explícitamente su arraigo territorial y sus interdependencias con el entorno. La segunda explora de

qué modo pueden integrarse los principios de la termoeconomía en las ciencias de la gestión para evaluar la eficiencia en el uso de recursos y la sostenibilidad organizacional desde una perspectiva físicamente fundamentada. La tercera aborda cómo diseñar una metodología basada en datos para la Evaluación Social del Ciclo de Vida Organizacional que reduzca la subjetividad y mejore la comparabilidad entre organizaciones y contextos. La cuarta examina en qué medida la combinación de perspectivas geoantropológica, termoeconómica y social data-driven permite avanzar hacia una gestión integrada de la sostenibilidad sistémica y la agilidad en cadenas de suministro manufactureras alineadas con los principios de la Industria 5.0.

De la pregunta general y de estas cuatro cuestiones específicas se derivan los objetivos de la tesis. El objetivo central consiste en desarrollar y validar marcos teórico-metodológicos innovadores para implementar la sostenibilidad sistémica en contextos de manufactura avanzada, en el marco del paradigma emergente de la Industria 5.0 y su proyección hacia la Industria 6.0, con el fin de gestionar eficazmente la complejidad de las cadenas de suministro mediante enfoques transdisciplinares, termoeconómicos y basados en datos que sean compatibles con la agilidad organizacional. A partir de este objetivo integrador se formulan cuatro objetivos específicos: (1) explorar la aplicabilidad del enfoque geoantropológico como lente estratégica transdisciplinar para comprender y evaluar la sostenibilidad sistémica en distritos industriales; (2) desarrollar un modelo teórico que integre principios termoeconómicos en las ciencias de la gestión, dando lugar a un sistema de Gestión Sistémica de la Exergía (SYMΞX) como herramienta flexible para la evaluación de la sostenibilidad; (3) diseñar una metodología basada en datos para la Evaluación Social del Ciclo de Vida Organizacional (SO-LCA data-driven) que minimice la subjetividad y mejore la comparabilidad de resultados; y (4) validar empíricamente los marcos propuestos mediante su aplicación al distrito cerámico italiano, demostrando su utilidad práctica para directivos, responsables de políticas públicas y académicos.

Metodológicamente, la investigación adopta un enfoque genuinamente transdisciplinar. La tesis integra conceptos y métodos procedentes de la geoantropología, la termoeconomía, las ciencias de la gestión, la evaluación del ciclo de vida, la estadística avanzada y el análisis de sistemas complejos. En lugar de aplicar estas perspectivas en paralelo, se buscan síntesis conceptuales y metodológicas que den lugar a marcos híbridos que ya no pertenecen por completo a ninguna disciplina aislada. Esta integración se materializa en un programa de investigación articulado en tres grandes bloques que corresponden uno a uno a los tres artículos del compendio, y que combinan construcción teórica, diseño metodológico y validación empírica.

El primer artículo se centra en la construcción del marco conceptual transdisciplinar a través de la geoantropología como lente estratégica. Mediante una revisión sistemática de la literatura, análisis documental de fuentes sectoriales y territoriales y razonamiento abductivo, se propone un enfoque que interpreta los distritos industriales como sistemas socio-técnico-territoriales donde se entrelazan personas, empresas, instituciones, territorio y ecosistemas. El distrito cerámico italiano de Sassuolo, principal polo europeo de producción de baldosas cerámicas, se analiza como caso paradigmático de sistema productivo intensivo en energía térmica y en consumo de materias primas minerales, con elevada orientación exportadora y fuerte vinculación al territorio. Este análisis permite identificar siete dimensiones clave de la sostenibilidad sistémica: consumo de recursos, dinámicas de producción, innovación, impacto ambiental, impacto social, dinámicas de mercado e impacto económico, y desarrollar un análisis de contingencia que incorpora eventos históricos y shocks exógenos. Sobre esta base, se propone un índice de sostenibilidad sistémica derivado de insights geoantropológicos como herramienta para medir y monitorizar la evolución del sistema, ofreciendo un soporte potencial para decisiones estratégicas en cadenas de suministro complejas de alto impacto material y energético.

El segundo artículo desarrolla el framework termoeconómico “Systemic Exergy Management” (SYMΞX), que integra la lógica exergética en el análisis de la sostenibilidad organizacional. A partir de una revisión exhaustiva de la literatura en termodinámica, termoeconomía y gestión empresarial, y mediante síntesis conceptual y razonamiento teórico-deductivo, se argumenta que el concepto de exergía, entendida como la cantidad máxima de trabajo útil que puede obtenerse de un sistema, ofrece una base física más adecuada que la energía total o que las métricas puramente monetarias para evaluar la eficiencia y la presión sobre los recursos naturales. SYMΞX propone extender el análisis exergético más allá de los sistemas energéticos tradicionales, conceptualizando diversos recursos organizacionales (materiales, energéticos, humanos, tecnológicos y relacionales) como "reservorios" cuya degradación puede medirse y gestionarse. El framework establece principios para el diseño de indicadores de desempeño basados en exergía que integran dimensiones ambientales, económicas, sociales y tecnológicas, y plantea su uso como complemento de herramientas existentes como el Análisis de Ciclo de Vida o el reporting ESG, abriendo vías para una gestión más informada de la sostenibilidad y la resiliencia de las cadenas de suministro, especialmente en sectores industriales intensivos en recursos como el cerámico.

El tercer artículo desarrolla y valida empíricamente una metodología de Evaluación Social del Ciclo de Vida Organizacional basada en datos (SO-LCA data-driven) aplicada nuevamente al sector cerámico italiano. La metodología se diseña en coherencia con las directrices del Programa de las Naciones Unidas para el Medio Ambiente (UNEP) en materia de Social Life Cycle Assessment y con los requisitos emergentes de reporting y debida diligencia social en el contexto europeo. Se define un conjunto estructurado de indicadores sociales que cubren, entre otras, las dimensiones de condiciones laborales, salud y seguridad, formación y desarrollo de competencias, diversidad e inclusión, relación con la comunidad local y derechos humanos en la cadena de suministro. Para reducir la subjetividad y mejorar la comparabilidad, se emplea Análisis de Componentes Principales para identificar factores latentes y reducir la dimensionalidad del sistema de indicadores, y normalización sigmoide para transformar variables heterogéneas en escalas comparables. La aplicación a una empresa del distrito cerámico, con datos organizacionales internos, permite construir índices sintéticos de desempeño social y evaluar su alineamiento con las expectativas de los principales grupos de interés, proporcionando información relevante para la gestión, para el cumplimiento regulatorio y para la agilidad organizacional en su dimensión humano-céntrica.

En términos de resultados, la tesis muestra, en primer lugar, que la perspectiva geoantropológica proporciona una comprensión más rica y matizada de la sostenibilidad sistémica en distritos industriales. El análisis del distrito cerámico italiano evidencia la interdependencia entre las siete dimensiones identificadas y cómo su evolución ha sido afectada por cambios tecnológicos, reestructuraciones productivas, crisis económicas y transformaciones regulatorias. El índice de sostenibilidad sistémica propuesto permite sintetizar esta complejidad en una métrica comprensible, capturando no solo niveles absolutos, sino también el equilibrio entre dimensiones, y ofreciendo una herramienta útil para diagnosticar fortalezas y debilidades, priorizar intervenciones y monitorizar tendencias en un sector industrial particularmente expuesto a las exigencias de descarbonización y circularidad.

En segundo lugar, la investigación demuestra que el framework SYMΞX abre un espacio conceptual fértil para integrar la termoeconomía en la gestión empresarial. Al hacer explícitos los costes en términos de destrucción de exergía asociados a diferentes configuraciones productivas, el enfoque permite reinterpretar resultados que, desde una óptica puramente financiera, podrían parecer equivalentes, pero que difieren sustancialmente en su impacto sobre los recursos físicos. SYMΞX sugiere que decisiones organizacionales que optimizan beneficios a corto plazo pueden implicar tasas elevadas de destrucción de exergía, debilitando la resiliencia a largo plazo de cadenas de suministro intensivas en recursos. A la inversa, inversiones en eficiencia exergética pueden fortalecer simultáneamente competitividad económica, sostenibilidad ambiental y capacidad de adaptación ante shocks, contribuyendo a formas de agilidad más profundas y sostenibles, especialmente relevantes en industrias de alto consumo energético como la cerámica.

En tercer lugar, la validación de la metodología SO-LCA data-driven en el sector cerámico italiano evidencia que es posible evaluar la dimensión social de la sostenibilidad con un grado de rigor y comparabilidad superior al de enfoques tradicionales dominados por juicios cualitativos. Los resultados empíricos permiten identificar “puntos calientes” sociales –por ejemplo, ámbitos donde la formación, las condiciones laborales o la seguridad requieren atención prioritaria– y contrastar la situación interna de la organización con las expectativas de distintos grupos de interés. La metodología se revela, además, como una herramienta útil para apoyar el cumplimiento de las crecientes exigencias regulatorias en materia de reporting social y de debida diligencia en la cadena de suministro, así como para orientar estrategias ESG coherentes con el paradigma de Industria 5.0 y con una visión ágil y humano-céntrica de la gestión empresarial.

La síntesis integradora de los tres artículos confirma que la sostenibilidad sistémica puede operacionalizarse mediante un conjunto coherente de marcos conceptuales y herramientas complementarias. El enfoque geoantropológico aporta la dimensión territorial y contextual; SYMΞX introduce la fundamentación físico-termodinámica; y la metodología SO-LCA data-driven cubre de manera rigurosa la dimensión social. En conjunto, estos marcos permiten abordar de forma integrada las dimensiones económica, ambiental, social y tecnológica, conectando niveles micro (empresa), meso (distrito industrial y cadena de suministro) y macro (paradigmas industriales y marcos regulatorios). La tesis muestra que la sostenibilidad sistémica no es incompatible con la agilidad organizacional; por el contrario, puede reforzarla al promover estructuras, procesos y relaciones más resilientes, fundamentadas en una gestión responsable de recursos físicos, humanos y sociales, y mejor preparadas para responder de forma flexible ante entornos cambiantes.

Como conclusiones generales, la tesis constata que: (i) la sostenibilidad sistémica constituye un marco más adecuado que el triple bottom line clásico para comprender y gestionar la sostenibilidad en cadenas de suministro complejas; (ii) el arraigo territorial de los sistemas productivos no es un elemento accesorio, sino un componente estructural que debe incorporarse explícitamente en el análisis, especialmente en distritos industriales de alta intensidad material y energética como el sector cerámico italiano; (iii) la integración de principios termodinámicos, en particular el análisis exergético, en la gestión empresarial ofrece una base física robusta para evaluar la eficiencia y los límites de los sistemas productivos; (iv) la dimensión social de la sostenibilidad puede evaluarse de manera cuantitativa y basada en datos, reduciendo la subjetividad y mejorando la comparabilidad; y (v) la combinación de perspectivas geoantropológica, termoeconómica y social data-driven proporciona un camino prometedor para articular sostenibilidad sistémica y agilidad organizacional en el marco de Industria 5.0. La investigación reconoce sus propias limitaciones, especialmente en cuanto al alcance de la validación empírica y a la necesidad de extender los marcos a otros sectores y contextos geográficos, y propone una agenda amplia de líneas futuras que incluye estudios comparativos internacionales, desarrollos metodológicos adicionales e integración con enfoques de economía circular y transformación digital. En conjunto, la tesis contribuye a la construcción de sistemas productivos más resilientes, humano-céntricos y genuinamente sostenibles, proporcionando a la vez bases conceptuales sólidas y herramientas operativas para avanzar en esa dirección.

ABSTRACT

Systemic Sustainability and Agility as New Organizational Paradigms for Managing Complexity in Supply Chains

This doctoral dissertation investigates systemic sustainability and organizational agility as a joint paradigm for managing complexity in manufacturing supply chains in the transition from Industry 4.0 to 5.0 and towards 6.0. As climate, resource, social, and supply-chain pressures intensify, they expose the limits of digitally advanced but narrowly financial Industry 4.0 models. Systemic sustainability is framed as a holistic view in which economic, environmental, social, and technological dimensions co-evolve, while agility characterizes a dynamic capability to reconfigure resources and relationships without losing alignment with long-term sustainability goals. The thesis comprises a compendium of three peer-reviewed articles, conceived as interconnected research blocks that jointly address one core question: how can systemic sustainability in manufacturing be conceptualized and analyzed so that it becomes a practical basis for decision-making in complex, agile supply chains? Four themes structure the work: (i) the territorial embeddedness of industrial districts; (ii) the integration of thermoeconomic principles into management; (iii) the design of a data-driven Social Organizational Life Cycle Assessment (SO-LCA); and (iv) the combined contribution of these perspectives to integrated management of sustainability and agility under Industry 5.0.

The empirical focus is the Italian ceramic district of Sassuolo, Europe's leading ceramic tile cluster and a highly energy- and resource-intensive industrial ecosystem, which serves as a representative testbed for the proposed frameworks. The first article develops a geoanthropological framework that interprets industrial districts as socio-technical-territorial systems. Applied to the ceramic district, it identifies seven key dimensions of systemic sustainability, analyzes their evolution under technological change and crises, and proposes a geoanthropology-informed systemic sustainability index as a diagnostic and monitoring tool.

The second article presents the thermoeconomic framework Systemic Exergy Management (SYMΞX). Building on thermodynamics, thermoeconomics, and management, it argues that exergy, defined as the maximum useful work obtainable from a system, offers a more appropriate physical basis than energy totals or purely monetary metrics for assessing efficiency and the pressure on natural resources. SYMΞX extends exergy analysis beyond classical energy systems and formulates principles for exergy-based performance indicators integrating environmental, economic, social, and technological dimensions. The third article designs and validates a data-driven SO-LCA methodology for the ceramic sector, aligned with UNEP guidelines and emerging European ESG and due diligence requirements. Using internal organizational data, Principal Component Analysis, and sigmoid normalization, it constructs synthetic indices of social performance and identifies social "hotspots" relevant for both regulatory compliance and human-centric agile management.

Overall, the thesis shows that systemic sustainability can be operationalized through a coherent set of complementary frameworks, namely a geoanthropological approach, the SYMΞX framework, and a data-driven SO-LCA methodology, that jointly address economic, environmental, social, and technological dimensions and link micro (firm), meso (district and supply chain), and macro (industrial paradigm and regulation) levels. The conclusions highlight that systemic sustainability and organizational agility are not antagonistic but mutually reinforcing, particularly in energy- and resource-intensive sectors such as the Italian ceramic industry.

Keywords: *Systemic sustainability, Industry 5.0, Industry 6.0, Geoanthropology, Thermoeconomics, Exergy management, Social Life Cycle Assessment, Supply chain complexity, Industrial districts, Organizational agility, ESG compliance, Ceramic sector*

RIASSUNTO

Sostenibilità Sistemica e Agilità come Nuovi Paradigmi Organizzativi per Gestire la Complessità nelle Catene di Fornitura

Questa tesi di dottorato indaga la sostenibilità sistemica e l'agilità organizzativa come paradigma congiunto per la gestione della complessità nelle catene di fornitura manifatturiere nella transizione da Industry 4.0 a Industry 5.0 e verso Industry 6.0. L'intensificarsi delle pressioni climatiche, ambientali, sociali e lungo le supply chain mette in evidenza i limiti di modelli di Industry 4.0 digitalmente avanzati ma concentrati in modo ristretto sulla performance finanziaria di breve periodo. La sostenibilità sistemica viene inquadrata come una visione olistica in cui le dimensioni economica, ambientale, sociale e tecnologica coevolvono, mentre l'agilità è trattata come una capacità dinamica di riconfigurare risorse e relazioni senza perdere l'allineamento con obiettivi di sostenibilità di lungo termine. La tesi si presenta come un compendio di tre articoli sottoposti a revisione paritaria, concepiti come blocchi di ricerca interconnessi. Nel loro insieme affrontano una domanda centrale: in che modo la sostenibilità sistemica nei contesti manifatturieri può essere concettualizzata e analizzata affinché diventi una base operativa per il decision-making in catene di fornitura complesse e agili? Quattro temi strutturano il lavoro: (i) il radicamento territoriale dei distretti industriali; (ii) l'integrazione dei principi termoeconomici nelle scienze di gestione; (iii) la progettazione di una metodologia di Social Organizational Life Cycle Assessment (SO-LCA) basata sui dati; e (iv) il contributo congiunto delle prospettive geoantropologica, termoeconomica e social data-driven alla gestione integrata di sostenibilità e agilità nel quadro di Industry 5.0.

Il fulcro empirico è il distretto ceramico italiano di Sassuolo, principale cluster europeo di piastrelle ceramiche e sistema industriale ad alta intensità energetica e di risorse, che funge da banco di prova rappresentativo per i framework proposti. Il primo articolo sviluppa un framework geoantropologico che interpreta i distretti industriali come sistemi socio-tecnico-territoriali. Applicato al distretto ceramico, identifica sette dimensioni chiave della sostenibilità sistemica, ne analizza l'evoluzione sotto l'effetto di cambiamenti tecnologici e crisi, e propone un indice di sostenibilità sistemica ispirato alla geoantropologia come strumento di diagnosi e monitoraggio.

Il secondo articolo presenta il framework termoeconomico Systemic Exergy Management (SYMΞX). Basandosi su termodinamica, termoeconomia e management, sostiene che l'exergia, intesa come la massima quantità di lavoro utile ottenibile da un sistema, offra una base fisica più adeguata dei soli bilanci energetici o delle metriche puramente monetarie per valutare efficienza e pressione sulle risorse naturali. SYMΞX estende l'analisi exergetica oltre i sistemi energetici classici e formula principi per indicatori di performance basati sull'exergia che integrano dimensioni ambientali, economiche, sociali e tecnologiche. Il terzo articolo progetta e valida una metodologia SO-LCA data-driven per il settore ceramico, allineata alle linee guida UNEP e ai requisiti ESG e di due diligence emergenti in Europa. Utilizzando dati organizzativi interni, Analisi delle Componenti Principali e normalizzazione sigmoide, costruisce indici sintetici di performance sociale e individua "hotspot" sociali rilevanti sia per la conformità regolatoria sia per una gestione agile e human-centric.

Nel complesso, la tesi mostra che la sostenibilità sistemica può essere resa operativa attraverso un insieme coerente di tre framework complementari: un approccio geoantropologico, il framework SYMΞX e una metodologia SO-LCA data-driven, che affrontano congiuntamente le dimensioni economica, ambientale, sociale e tecnologica e collegano i livelli micro (impresa), meso (distretto e catena di fornitura) e macro (paradigma industriale e regolazione). Le conclusioni mettono in evidenza che sostenibilità sistemica e agilità organizzativa non sono antagoniste, ma si rafforzano reciprocamente, in particolare nei settori ad alta intensità di energia e risorse come l'industria ceramica italiana.

Parole chiave: *Sostenibilità sistemica, Industria 5.0, Industria 6.0, Geoantropologia, Termoeconomia, Gestione dell'exergia, Valutazione Sociale del Ciclo di Vita, Complessità della catena di fornitura, Distretti industriali, Agilità organizzativa, Compliance ESG, Settore ceramico*

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PART I – INTRODUCTORY FRAMEWORK

1 GENERAL INTRODUCTION

1.1 Motivation and justification of the research

The industrial transformation occurring in the first decades of the twenty-first century marks an unprecedented turning point in the history of manufacturing. Industry 4.0 can be understood as a paradigm oriented toward operational performance, in which digitalization, automation, and interconnection primarily serve efficiency, productivity, real-time control, and greener production. Industry 5.0 broadens this logic toward human-centric, sustainable, and resilient performance, integrating technological development with ESG criteria and aligning productivity with human and environmental priorities. Industry 6.0 represents a holistic approach in which advanced data analytics and adaptive capabilities support systemic sustainability as a key organizational strategy, generating competitive advantage through systemic value creation while strengthening agility and resilience. In this sense, the evolution from Industry 4.0 to Industry 5.0 and Industry 6.0 is not treated merely as a sequence of technological stages but as a progressive expansion of expected industrial performance: from operational efficiency and greener production to human-centric value creation and, finally, toward systemic sustainability. Against this background, this thesis examines systemic sustainability and organizational agility as complementary paradigms for managing complexity in manufacturing supply chains (Barata & Kayser, 2023; Duggal et al., 2022).

This transformation is not merely technological. Contemporary supply chains face unparalleled levels of complexity, characterized by market globalization, demand volatility, scarcity of natural resources, growing environmental and social regulatory pressures, and increasingly demanding stakeholder expectations (Varriale et al., 2023). The COVID-19 pandemic has further exposed the fragility of hyper-connected production systems that lack systemic resilience (Ikram et al., 2020).

Against this backdrop, traditional management approaches, focused predominantly on maximizing economic and financial value, prove insufficient (Kakogiannis, 2024; Spash, 2020). It becomes imperative to develop new theoretical and methodological frameworks that enable organizations to navigate the inherent complexity of contemporary production systems while integrating economic, environmental, social, and technological dimensions simultaneously. In this context, the concept of systemic sustainability emerges as an innovative organizational paradigm (Khlif et al., 2022).

Systemic sustainability goes beyond conventional approaches to corporate sustainability. Whereas traditional models tend to address the economic, environmental, and social dimensions in a fragmented way, treating them as independent pillars of the triple bottom line (Srivastava et al., 2022), systemic sustainability recognizes the interconnected and co-evolving nature of these elements. It adopts a holistic perspective, viewing organizations not as isolated entities but as complex adaptive systems embedded in broader networks of relations with territories, communities, ecosystems, and value chains (West et al., 2020).

This doctoral research stems from the conviction that systemic sustainability, combined with organizational agility, constitutes the necessary paradigm for manufacturing firms to manage the complexity of modern supply chains. In this context, organizational agility refers to the capability of firms to sense and anticipate changes in their environment, rapidly reconfigure their resources and processes, and do so without losing alignment with systemic sustainability objectives (Dimple & Tripathi, 2024). Through a transdisciplinary approach that integrates perspectives from geoanthropology, thermoeconomics, management sciences, and life cycle assessment, this thesis seeks to contribute to the development of theoretical frameworks and methodological tools that support the transition towards more resilient, human-centric, and genuinely sustainable industrial models.

In summary, the central problem addressed in this thesis is how to operationalize systemic sustainability alongside organizational agility in complex manufacturing contexts and advanced supply chains, so that the resulting frameworks are both conceptually rigorous and practically helpful for managerial decision-making.

1.2 Objectives of the thesis

This research aims to develop and validate innovative theoretical-methodological frameworks for implementing systemic sustainability in advanced manufacturing contexts within the emerging Industry 5.0 paradigm and its projection towards Industry 6.0, to effectively manage supply chain complexity through transdisciplinary, thermoeconomic, and data-driven approaches. To this end, the research formulates a primary integrative objective, from which several specific objectives are derived and articulated across the three articles that compose the compendium.

First, the overarching objective is to establish the theoretical and practical connections among the proposed frameworks, demonstrating how their integration contributes to the holistic management of systemic sustainability in high-complexity supply chains. This integrative objective is essential to ensure that the individual contributions of each article cohere into a comprehensive and consistent vision of systemic sustainability.

Building on this integrative aim, the thesis defines four additional specific objectives. Second, it explores the applicability of a geoanthropological approach as a strategic transdisciplinary lens for understanding and assessing systemic sustainability in industrial districts (Renn, 2022). To address this objective, the analysis focuses on the complex interactions among people, territory, technology, and the production environment in the transition towards Industry 5.0 and 6.0, recognizing that specific territorial contexts shape how production systems operate and evolve their sustainability trajectories.

Third, the research aims to develop an innovative theoretical framework that integrates thermoeconomic principles into management sciences, proposing Systemic Exergy Management (SYMΞX) as a flexible tool for measuring resource-use efficiency and evaluating sustainability performance (Dincer, 2002). This objective responds to the need to move beyond purely financial metrics by incorporating rigorous physical foundations that acknowledge the thermodynamic laws governing all resource transformation processes.

Fourth, the thesis proposes to develop a data-driven methodology for Social Organizational Life Cycle Assessment (SO-LCA) that minimizes the subjectivity characteristic of previous approaches, improves the comparability of results across organizations and contexts, and facilitates the integration of the social dimension into corporate sustainability strategies and compliance with environmental, social, and governance (ESG) requirements in the context of Industry 5.0 (García-Muiña et al., 2022; Tokede & Traverso, 2020). The social dimension of sustainability, historically less developed than the environmental and economic dimensions, calls for rigorous methodological tools that enable its systematic assessment.

Fifth, the thesis aims to empirically validate the proposed frameworks by applying them to the Italian ceramic district, demonstrating their practical usefulness for managers, policymakers, and academics interested in industrial sustainability. This empirical validation is essential to ensure that theoretical developments do not remain at an abstract level but become tools applicable in real-world contexts.

The thesis pursues these objectives in an integrated manner across the three articles that comprise the compendium. The second objective is primarily addressed in Article 1 (geoanthropological approach), the third in Article 2 (SYMΞX framework), and the fourth in Article 3 (data-driven SO-LCA methodology). The fifth objective is realized through the empirical application to the Italian ceramic district. In contrast, the integrative objective underpins the whole and articulates the theoretical and practical integration of the three proposed frameworks. The state-of-the-art section explicitly presents the research questions that operationalize these objectives, in direct connection with the gaps identified in the literature.

1.3 State of the Art

This section presents the theoretical framework underpinning the dissertation and structures the literature review into four main blocks. First, it examines the evolution of the concept of sustainability towards systemic sustainability, along with its main theoretical approaches. Second, it analyses the growing complexity of supply chains and the role of the Industry 5.0 paradigm in the transition towards more sustainable and resilient production models. Finally, it synthesizes the main gaps identified in the literature and explicitly derives the research questions that guide the thesis objectives.

1.3.1 Systemic sustainability: definition and theoretical approaches

The concept of sustainability has undergone a significant evolution since its popularization with the Brundtland Report in 1987. The classic definition of "sustainable development" as development that meets the needs of the present without compromising the ability of future generations to meet their own needs has been the starting point for countless academic approaches and business practices. However, operationalizing this concept has faced considerable challenges, particularly in integrating its constituent dimensions (Kakogiannis, 2024; Spash, 2020).

The triple bottom line model, proposed by Elkington in the late 1990s, represented a significant step forward by explicitly articulating the three dimensions of sustainability: economic, environmental, and social. This approach has been widely adopted in the corporate sphere and has inspired numerous sustainability reporting and assessment frameworks. Nevertheless, recent research has highlighted fundamental limitations of this perspective, especially its tendency to treat the three dimensions as separate and independent "pillars" when they are deeply interconnected through non-linear relationships and feedback loops (Srivastava et al., 2022).

Systemic sustainability emerges as a necessary evolution that overcomes the limitations of the traditional triple bottom line. From a systemic perspective, organizations are not isolated entities that can optimize their economic, environmental, and social performance independently, but rather complex adaptive systems embedded in broader relationship networks (Pascarella & Bednar, 2022; Tong et al., 2018). This view recognizes that the dimensions of sustainability are interconnected and that organizations co-evolve with their territorial, social, and environmental contexts. The impacts of organizational decisions propagate across multiple spatial and temporal scales, generating emergent effects that cannot be predicted by analyzing isolated components. Therefore, assessing sustainability solely through financial or even conventional environmental indicators is insufficient; it requires metrics that capture the system's health, recognize interdependencies, and consider extended time horizons (Tong et al., 2018; Villeneuve et al., 2017).

The literature on systems thinking applied to sustainability has grown substantially over the last decade. In manufacturing contexts, the application of these principles has given rise to approaches such as industrial ecology, industrial symbiosis, and circular economy models, all of which share a systemic view of material, energy, and information flows (Bressanelli et al., 2022; Rosa & Beloborodko, 2015; Walker et al., 2021). These approaches recognize that the waste of one production process can constitute valuable resources for another, that local optimization of isolated components may result in sub-optimization of the overall system, and that the resilience of the whole system requires diversity, strategic redundancy, and adaptive capacity (Bressanelli et al., 2022; Walker et al., 2021). In this context, organizational agility can be understood as an operational manifestation of this adaptive capacity, enabling organizations to rapidly adjust their structures and processes without losing sight of the systemic interdependencies on which sustainability is built (Dimple & Tripathi, 2024).

1.3.2 Complexity in supply chains and the need for new paradigms

Unprecedented levels of complexity characterize contemporary supply chains. This complexity is multidimensional and manifests itself in several interrelated aspects that challenge traditional management paradigms. Structural complexity arises from the fact that modern supply chains involve networks of suppliers, manufacturers, distributors, and customers dispersed globally, with multiple supply tiers and configurations that change dynamically in response to market conditions, resource availability, and strategic decisions. Achieving full traceability of products and materials across these networks is highly challenging, particularly when social and environmental sustainability factors are considered at deeper tiers of the chain (Govindan et al., 2021; Varriale et al., 2023).

To this structural complexity, we must add dynamic complexity, generated by globalized markets that produce volatile and unpredictable demand patterns. Product life cycles are progressively shortening, expectations of customization are growing exponentially, and disruptive events such as health crises, geopolitical conflicts, and natural disasters intensified by climate change can radically alter operating conditions in very short periods. This inherent volatility requires rapid adaptation, a capability many organizations lack (Santiago et al., 2025).

Decision-making complexity constitutes another fundamental dimension. Organizations must make decisions while simultaneously considering multiple objectives that are often in tension with one another. Optimizing cost may compromise quality or lead time; maximizing production efficiency may generate negative environmental impacts or deteriorate working conditions; prioritizing environmental sustainability may increase costs or reduce flexibility. Decision-makers must operate under conditions of significant uncertainty and frequently incomplete or asymmetric information among supply chain actors (Beiragh et al., 2020).

Regulatory complexity adds a layer of challenge. The regulatory framework on sustainability has become progressively more demanding and diversified, with regulations covering issues ranging from greenhouse gas emissions to human rights in the supply chain, and including circular economy, biodiversity, transparency, and ESG reporting. These regulations vary significantly across jurisdictions, creating challenges for organizations operating globally (European Commission, 2021).

In the face of this multifaceted complexity, traditional operations and supply chain management paradigms show essential limitations. Approaches based on deterministic optimization assume stable and predictable conditions that rarely hold in practice. Linear forecasting techniques are inadequate for systems characterized by nonlinearity, critical thresholds, and emergent behavior. Hierarchical, centrally controlled models lack the flexibility required to respond rapidly to local perturbations. Consequently, it becomes necessary to move towards new organizational paradigms that integrate rapid adaptation capabilities, resilience, systems thinking, long-term orientation, and multi-stakeholder approaches (Ivanov, 2023; Mahajan et al., 2023), aligned with the systemic sustainability perspective developed in this thesis. Within this framework, the thesis defines organizational agility as a structural dynamic capability that enables firms to rapidly reconfigure processes, relationships, and flows without losing alignment with systemic sustainability objectives, going beyond purely tactical, short-term responses to disruptions (Dimple & Tripathi, 2024; Smuts & Van der Merwe, 2022).

1.3.3 From Industry 5.0 to Industry 6.0 in the sustainable transition

Industry 5.0 represents a paradigm shift from its predecessor, going beyond mere incorporation of new technologies. Whereas Industry 4.0 emphasized the digitalization, automation, and interconnection of production systems with the primary objective of increasing efficiency and productivity, Industry 5.0 proposes a more balanced vision that places the human being at the center of the production system and explicitly prioritizes sustainability and resilience as core, rather than secondary, objectives (Barata & Kayser, 2023; Ivanov, 2023).

In its 2021 communication on Industry 5.0, the European Commission articulates a vision grounded in three fundamental pillars that reorient industrial development. The human-centric pillar recognizes that technology must serve people, not the other way around. It implies designing production systems that enhance human capabilities, guarantee safe and decent working conditions, promote skills development throughout working life, and respect diversity in all its forms. This approach contrasts with technological visions in which automation progressively replaces the human factor.

The sustainability pillar goes beyond eco-efficiency to embrace an integral vision that includes circularity in the use of materials, minimization of environmental impacts across the entire life cycle of products and processes, active contribution to the United Nations Sustainable Development Goals, and explicit consideration of planetary boundaries that humanity cannot transgress without risking ecological collapse. This understanding of sustainability recognizes that governments and firms cannot pursue economic growth at the expense of the stability of the natural systems on which human life depends (Atif, 2023; Panza et al., 2023).

The resilience pillar seeks to create production systems capable of adapting to shocks and maintaining essential functions under disruption, through diversification of supply sources, strategic redundancy in critical capacities, adaptive autonomy of subsystems, and intensive collaboration among actors. The COVID-19 pandemic has dramatically shown that extreme optimization for efficiency can generate systemic fragility, and that resilience requires investment in capabilities that may appear redundant in normal times but prove essential in critical moments (Ghobakhloo et al., 2023; Ivanov, 2023). In practice, the combination of resilience and sustainability in Industry 5.0 environments rests on the development of agile organizations and supply chains that can rapidly reconfigure their operations and relationships without compromising human centrality or sustainability commitments (Carayannis & Morawska-Jancelewicz, 2022; Gigauri & Janjua, 2023).

The transition towards Industry 5.0 does not entail abandoning Industry 4.0 technologies, but rather reorienting them towards broader, more balanced objectives. Digital technologies such as the Internet of Things (IoT), artificial intelligence, digital twins, blockchain, and augmented reality become enablers of systemic sustainability when organizations use them with a clear purpose: optimizing resource use, ensuring full traceability in supply chains, enabling sustainable product customization that meets individual needs without massive waste, fostering industrial symbiosis that transforms waste into resources, and supporting radical transparency in ESG reporting that allows stakeholders to make informed decisions (Asif et al., 2023; García-Muiña et al., 2021).

In this evolving context, some authors have begun to explore the concept of Industry 6.0 as a forward-looking projection that incorporates even more disruptive elements, including advanced autonomy, quantum-enabled processes, bioengineering applications, and new forms of production organization. Although some of these developments remain prospective, they highlight the open and evolving nature of industrial paradigms and the importance of developing conceptual frameworks that are sufficiently flexible and adaptive to accommodate future transformations (Das & Pan, 2022; Duggal et al., 2022).

Accordingly, the distinction among Industry 4.0, Industry 5.0, and Industry 6.0 can be understood not only in technological terms but also in the performance logic they prioritize. Industry 4.0 is primarily associated with operational performance, emphasizing efficiency, productivity, automation, real-time control, and greener production. Industry 5.0 broadens this logic by incorporating human-centric, sustainable, and resilient performance, integrating ESG-oriented value creation with the alignment between productivity and human and environmental priorities. Industry 6.0, as explored in this thesis, further extends this perspective toward systemic sustainability, in which value creation is assessed across interconnected firms, supply chains, territories, stakeholders, and natural systems. This transition is central to the thesis because it justifies the need for frameworks capable of measuring not only efficiency but also resource degradation, social impacts, territorial embeddedness, and long-term sustainability (Barata & Kayser, 2023; Duggal et al., 2022; Ivanov, 2023).

1.3.4 Research gaps in the scientific literature

Based on the systematic literature review, the analysis identifies several main gaps or limitations that justify and guide this doctoral research. On this basis, one overarching, broad, and systemic research question (Q1) is articulated, from which four specific questions (Q2–Q5) are derived, each addressing a concrete dimension of that general problem. These gaps and questions are closely interrelated and structure the development of the thesis.

First, there is a notable disconnect between theory and practice in systemic sustainability. Although the theoretical literature on systems thinking and sustainability is abundant and sophisticated, its translation into operational tools that managers can effectively use in real organizational contexts remains limited. Existing frameworks tend to remain at an abstract conceptual level, without providing clear guidance on how to implement them in practice, what data to collect, how to analyze them, and how to use the results to inform strategic and operational decisions (Kakogiannis, 2024; Villeneuve et al., 2017).

On this basis, the following overarching research question is posed:

Q1. *How can systemic sustainability in manufacturing production systems be conceptualized and analysed in ways that make it operationally useful for decision-making in complex supply chains?*

Second, the limited consideration of territorial context constitutes a significant gap. Much of the literature on corporate sustainability adopts an implicitly universalist perspective, proposing frameworks and "best practices" that supposedly apply across geographical, cultural, and institutional contexts. This perspective ignores how territorial, cultural, and historical factors deeply condition the possibilities and forms that sustainability can take. Industrial districts are specific forms of territorially embedded productive organization that combine sectoral specialization, geographical proximity, dense relational networks, and strong cultural identity. However, they have been little explored from the perspective of systemic sustainability, despite representing particularly rich contexts in which to apply approaches that recognize the territorial embeddedness of production (Bellandi et al., 2021; Hervas-Oliver & Boix, 2022).

From this gap, the second research question arises:

Q2. *How can systemic sustainability in manufacturing industrial districts be analyzed while explicitly incorporating their territorial embeddedness and interdependencies with the surrounding environment?*

Third, a persistent disconnect exists between thermoeconomics and business management. Although thermoeconomics, as a discipline, has developed valuable insights into resource efficiency and sustainability from fundamental physical perspectives, its application in the management domain remains scarce. There is significant potential to build conceptual bridges between these fields, translating thermodynamic principles and exergy analysis into tools relevant to organizational decision-making on investments, production processes, product design, and supply chain configuration (Dincer, 2002; Romero & Linares, 2014).

This gap leads to the third research question:

Q3. *How can thermoeconomic principles be integrated into management sciences to assess resource efficiency and organizational sustainability from a physically grounded perspective?*

Fourth, subjectivity in social assessment represents a critical gap. The social dimension of sustainability has historically received less academic and practical attention than its environmental and economic counterparts. Existing methodologies for social assessment, such as Social Life Cycle Assessment, suffer from significant subjectivity in the selection of indicators, weightings, and value judgements. The lack of systematic quantitative data on social impacts, combined with the heterogeneity of cultural and institutional contexts, has hindered the development of standardized and comparable metrics. This situation is particularly problematic at a time when regulatory requirements for social reporting and stakeholder expectations are growing exponentially (Blandino & Montagna, 2025; Huertas-Valdivia et al., 2020; Tokede & Traverso, 2020).

This gap gives rise to the fourth research question:

Q4. *How can a data-driven methodology for Organizational Social Life Cycle Assessment be designed that reduces subjectivity and improves the comparability of results across organizations and contexts?*

Fifth, the literature shows insufficient integration between systemic sustainability, organizational agility, and the emerging Industry 5.0 paradigm. Although research on supply chain agility has advanced notably in terms of response time, flexibility, and adaptive capacity, it rarely connects with sustainability frameworks that simultaneously consider economic, environmental, and social dimensions. At the same time, the emergent nature of Industry 5.0 means that consolidated theoretical and methodological frameworks for its implementation are still lacking, especially regarding the operational integration of its three pillars (human-centricity, sustainability, and resilience) in complex manufacturing contexts (Barata & Kayser, 2023; Ghobakhloo et al., 2023). Some recent works explicitly explore the intersection between agility, sustainability, and Industry 5.0, but they also underline the scarcity of established cases and tools in this field (Carayannis & Morawska-Jancelewicz, 2022; Gigauri & Janjua, 2023; Smuts & Van der Merwe, 2022).

This combination of gaps leads to a fifth, integrative research question:

Q5. *To what extent does the combination of geoanthropological, thermoeconomic, and data-driven social perspectives enable progress towards integrated management of systemic sustainability and agility in manufacturing supply chains aligned with the principles of Industry 5.0?*

In summary, the research questions Q1-Q5 are operationalized into the specific objectives defined in Section 1.2. Each article addresses one or more of these questions as a priority (Article 1: territorial and systemic perspective; Article 2: thermoeconomic integration; Article 3: data-driven social assessment), while the empirical application to the ceramic district and the final synthesis articulate these partial answers around the central issue posed in Q1.

1.4 Research methodology

This research adopts a genuinely transdisciplinary approach that goes beyond simple multidisciplinarity or interdisciplinarity. Whereas multidisciplinarity involves juxtaposing perspectives from multiple disciplines without deeply integrating them, and interdisciplinarity seeks connections between disciplines while preserving their separate identities, transdisciplinarity aspires to create conceptual and methodological syntheses that transcend traditional disciplinary boundaries. In this dissertation, concepts and methods from geoanthropology, thermoeconomics, management sciences, life cycle assessment, advanced statistics, and complex systems analysis are not applied merely in parallel; instead, they are integrated into innovative frameworks that inherit elements from all these traditions while not fully belonging to any single one.

Consistent with this approach, the research program structures the work not as a strict sequence of closed phases but as three successive and interrelated blocks, corresponding to the three articles that compose the compendium and addressing the specific objectives of the thesis. The first block focuses on developing the transdisciplinary conceptual framework, elaborated in the first article through a systematic literature review, documentary analysis, and theory building via abductive reasoning. This exploratory-interpretive approach seeks to establish broad conceptual foundations for the rest of the research, proposing the geoanthropological framework as a strategic lens for understanding systemic sustainability in Industry 5.0 contexts and for projecting it into Industry 6.0.

The second block contributes methodologically by developing the thermoeconomic framework presented in the second article. This part of the research combines an exhaustive literature review in both thermoeconomics and management studies with theory building through conceptual synthesis and abductive reasoning. The approach is predominantly theoretical-deductive, aiming to establish rigorous logical connections between fundamental thermodynamic principles and organizational management concepts, resulting in the SYMΞX framework as a flexible tool for sustainability assessment based on exergy analysis.

The contribution of the third block centers on the empirical validation and data-driven methodological application presented in the third article. This part of the research uses a case study methodology combined with the collection of primary organizational data and advanced statistical analysis, including Principal Component Analysis and sigmoid normalization. The approach is empirical-quantitative, aiming to demonstrate the practical feasibility of data-driven methodologies for Social Organizational Life Cycle Assessment in the Italian ceramic sector. Taken together, the three blocks of work complementarily cover conceptual construction, physical-theoretical grounding, and empirical testing of the proposed frameworks, constituting the methodological pathway through which the specific objectives set out in Section 1.2 are pursued and the overarching objective of the thesis is advanced.

The main empirical context of this research is the Italian ceramic district, specifically the Sassuolo cluster in the Emilia-Romagna region. This choice is not incidental but strategically grounded in multiple considerations. The Italian ceramic district is the largest European producer of ceramic tiles and one of the most important worldwide, with a strong export orientation and a consolidated reputation for technological excellence and product quality. This sectoral relevance ensures that the research findings have practical significance for an important segment of the European economy (Confindustria Ceramica, 2023).

The district constitutes a complex industrial ecosystem that includes not only tile manufacturers, but also specialized suppliers of machinery and equipment, raw materials and glazes, research and technological development centers, training institutions that prepare specialized professionals, and sectoral organizations that coordinate collective activities. This systemic complexity makes the district a particularly suitable case for applying systemic sustainability perspectives that recognize interdependencies and co-evolutionary dynamics (Cucchi et al., 2023; Mattioli, 2019).

Ceramic production poses significant sustainability challenges: it is highly energy-intensive in firing processes, consumes large volumes of natural raw materials, generates atmospheric emissions and solid waste, and relies on processes that have historically been difficult to decarbonize. These challenges make the ceramic sector a critical case for exploring transitions toward systemic sustainability, with lessons potentially transferable to other sectors facing similar material and energy-intensity challenges (Bignozzi et al., 2022; Cucchi et al., 2023).

The district combines a manufacturing tradition that dates back centuries of artisanal ceramic production with intensive adoption of technological innovation, including advanced automation, digitalization of processes, and exploration of Industry 4.0 technologies. This coexistence of tradition and innovation provides an ideal context for exploring how the transition toward Industry 5.0 can unfold in mature sectors with long historical trajectories, where innovation must be reconciled with consolidated sectoral identities and accumulated capabilities (Confindustria Ceramica, 2023; Hervas-Oliver & Boix, 2022). Finally, the strong link between productive activity, territory, and local community that characterizes the district makes it a particularly suitable case for applying geoanthropological perspectives that recognize the territorial nature of production systems. The district is not simply a geographic concentration of firms, but a socio-technical-territorial system in which production relations, cultural identities, local institutions, and geographical features tightly intertwine.

Data collection combines multiple sources and methods. Documentary analysis of secondary sources includes sectoral reports published by industrial associations, official statistical databases on production, employment, foreign trade, and economic performance, and corporate public documentation such as sustainability reports, annual reports, and corporate communications. The collection of internal organizational primary data, which is essential for the empirical validation in the third article, includes operational data on resource consumption, emissions, and production efficiency; labor data on employment, working conditions, training, and safety; and environmental data on waste management and water and energy use. Wherever possible, these quantitative data have been complemented with qualitative information to contextualize and nuance the results.

In addition, interviews were conducted with key sectoral informants, including corporate managers, trade association representatives, researchers from technological centers, and union representatives, alongside observation of production processes and organizational dynamics to capture aspects difficult to grasp from quantitative data or formal interviews alone.

The analytical techniques employed reflect the research's methodological diversity. Qualitative content analysis is used in the theoretical construction of the first and second articles to identify key concepts, establish conceptual relationships, and develop theoretical propositions through inductive and abductive reasoning. Principal Component Analysis is used in the third article to identify underlying factors in complex sets of social indicators, reducing dimensionality and revealing latent structures in the data. Sigmoid normalization enables the treatment of heterogeneous indicators with different units of measurement and ranges of variation, transforming them into comparable scales. Contingency analysis, particularly relevant in the first article, examines how specific contextual factors and historical events have affected the district's various dimensions of sustainability. Finally, the study develops synthetic sustainability indices that aggregate multiple indicators into comprehensive metrics that capture overall performance (Gee et al., 1997; Mohsine et al., 2023; Settanni, 2024), enabling comparisons, trend monitoring, and informed management and policy decisions.

1.5 Structure of the thesis and thematic unity

This doctoral thesis presents a compendium of publications, integrating three peer-reviewed academic journal articles that address complementary aspects of a unifying central theme: systemic sustainability as an organizational paradigm for managing complexity in supply chains in advanced manufacturing contexts. Each article functions as a work block that develops one or more of the specific objectives defined in Section 1.2, while their joint reading advances the overarching objective of articulating these frameworks into a coherent vision of systemic sustainability.

The first article, titled "Exploring Systemic Sustainability in Manufacturing: Geoanthropology's Strategic Lens Shaping Industry 6.0" and published in the Global Journal of Flexible Systems Management, primarily addresses the objective of exploring the applicability of a geoanthropological approach as a strategic lens for understanding systemic sustainability in industrial districts, while also providing a first step toward the conceptual integration required by the general objective of the thesis. The article introduces geoanthropology as an innovative perspective for analyzing systemic sustainability in manufacturing contexts, specifically in industrial districts, and proposes a transdisciplinary approach that integrates geoanthropological principles with the Industry 5.0 paradigm to project the emerging concept of Industry 6.0. It identifies seven key factors for assessing systemic sustainability: resource consumption, production dynamics, innovation, environmental impact, social impact, market dynamics, and economic impact. It also develops a contingency analysis that considers historical events and contextual factors specific to the ceramic district and proposes a systemic sustainability index derived from geoanthropological insights as a pragmatic tool to measure and guide the development of sustainability initiatives. Taken together, this first block situates the phenomenon in its territorial and historical context and defines the main analytical axes of the thesis.

The second article, titled "Thermoeconomics Meets Business Science: Systemic Exergy Management (SYMΞX) as a New Theoretical and Flexible Framework for Sustainability" and published in the Global Journal of Flexible Systems Management, develops the objective of creating an innovative theoretical framework that integrates thermoeconomic principles into management sciences, providing the physical and conceptual basis required for the research program. The article introduces the SYMΞX framework as a paradigm for measuring organizational performance that integrates thermoeconomic principles and shows how the concept of exergy, the maximum useful work obtainable from a system, offers a more precise thermodynamic measure than total energy for evaluating efficiency in transformation processes. SYMΞX focuses on measuring the effectiveness of organizational resource use through exergy analysis and supports the development of sustainability performance indicators that assess environmental, economic, social, and technological impacts. In this way, the article argues that SYMΞX offers a more comprehensive perspective on organizational performance by considering not only financial results but also resource efficiency and environmental impacts, thereby fostering systemic sustainability and opening new pathways for empirical validation and sector-specific applications.

The third article, titled *"Unlocking the Social Promise of Industry 5.0: Harnessing Data-Driven Social Life Cycle Assessment for Corporate Sustainability"* and published in *Corporate Social Responsibility and Environmental Management*, primarily addresses the objective of developing a data-driven methodology for Social Organizational Life Cycle Assessment while simultaneously contributing to the empirical validation objective through its application to the Italian ceramic district. In the context of Industry 5.0, characterized by the integration of digital technologies and human-centric approaches, evaluating social sustainability remains a critical challenge. The article explores the transformative potential of Social Life Cycle Assessment within the United Nations Environment Programme's stakeholder framework. The proposed methodology is both standardized and data-driven, employing advanced statistical techniques such as Principal Component Analysis and sigmoid normalization to minimize subjectivity and improve the comparability of results. Empirical validation through a case study in the Italian ceramic industry, using internal organizational data aligned with Organizational Social Life Cycle Assessment guidelines, demonstrates the practical feasibility of the approach and provides concrete evidence to support decision-making in social sustainability and ESG.

The thematic unity of these three articles is structured around the core concept of systemic sustainability, understood as an approach that is simultaneously holistic, by integrating economic, environmental, social and technological dimensions while recognizing their interconnections; contextual, by acknowledging the importance of territorial embeddedness and the specificity of productive contexts; physically grounded, by basing itself on thermodynamic principles that govern resource transformation processes; socially centered, by placing people and their relationships at the heart of the production system; measurable and manageable, by proposing concrete tools for evaluation and continuous improvement; and future-oriented, by aligning with emerging paradigms such as Industry 5.0 and 6.0 and evolving regulatory frameworks such as ESG. From this perspective, the Italian ceramic district serves as an empirical testing ground for the proposed frameworks and advances the thesis's objective of practical validation.

The articles follow a logical progression from broad conceptual frameworks to practical operationalization, consistent with the research's integrative objective. The first article establishes the strategic framework through a geoanthropological approach, clarifying the perspective from which systemic sustainability should be understood in complex industrial contexts. The second article provides rigorous theoretical grounding through SYMΞX, answering the question of how to measure efficiency and sustainability on a physically sound basis. The third article delivers practical operationalization by developing concrete, data-driven methodologies for assessing the social dimension of sustainability and empirically testing them in the ceramic district. Taken together, these three blocks establish theoretical and practical connections among the proposed frameworks and demonstrate how their integration contributes to more effective management of systemic sustainability in complex supply chains.

Overall, the three articles provide an integrated conceptual and methodological framework for operationalizing systemic sustainability in manufacturing organizations confronting the complexity of global supply chains and the transition toward more human-centric, resilient, and genuinely sustainable industrial models. This system does not merely compile independent contributions; rather, it forms a coherent architecture in which each article fulfills a specific function, namely contextualizing, grounding, and operationalizing. Together, they form a single research program aimed at answering the central question of how to operationalize systemic sustainability alongside organizational agility in complex manufacturing supply chains.

1.6 Scientific contribution of the research

This doctoral research makes several significant contributions, which can be grouped into three interrelated dimensions. At the theoretical level, it advances the conceptualization of systemic sustainability by developing an integrated framework that overcomes the limitations of the traditional triple bottom line by incorporating systems thinking, territorial perspectives, and thermodynamic grounding. This conceptual advance is not merely incremental; it represents a qualitative shift in how sustainability is understood and addressed in complex organizational contexts, especially when organizations must reconcile it with high levels of organizational agility in uncertain and dynamic environments.

Building a bridge between thermoeconomics and management constitutes a particularly innovative theoretical contribution. Historically, these two domains have evolved largely in parallel with limited interaction. Thermoeconomics has developed mainly in the context of energy systems and specific industrial processes, whereas management sciences have tended to adopt predominantly economic, financial, or socio-organizational perspectives. This thesis shows how fundamental thermodynamic principles, particularly the concept of exergy, can be systematically incorporated into reflection on organizational performance and sustainability, offering new perspectives that explicitly acknowledge the physical realities of resource transformation processes.

The enrichment of Industry 5.0 constitutes another significant theoretical contribution. Given the nascent nature of these paradigms, there is an urgent need to develop conceptual and methodological content that gives substance to principles that remain largely abstract. This research contributes to Industry 5.0 by helping to operationalize its central pillars, namely human centricity, sustainability, and resilience, through frameworks that connect organizational agility, social assessment, resource efficiency, and decision-making in complex manufacturing contexts. In this sense, the thesis clarifies that Industry 5.0 should not be understood as a rejection of Industry 4.0 technologies but as their reorientation toward broader performance objectives.

The exploration of the emerging Industry 6.0 paradigm constitutes a complementary theoretical contribution. While Industry 5.0 reframes industrial performance around human-centricity, sustainability, and resilience, this thesis approaches Industry 6.0 as a holistic projection in which systemic sustainability becomes a key organizational strategy for value creation, adaptability, and resilience. The thesis contributes to this clarification by showing how geoanthropological, thermoeconomic, and data-driven social perspectives can support a broader understanding of performance, moving beyond operational efficiency toward measurable impacts on resources, society, territory, and long-term sustainability.

Demonstrating the value of genuinely transdisciplinary approaches constitutes a higher-order methodological contribution. In an academic context often characterized by hyperspecialization and disciplinary fragmentation, this research illustrates how the deep integration of diverse perspectives, including geoanthropology, thermoeconomics, management sciences, and life cycle assessment, can generate insights and solutions that would not emerge from single-discipline approaches. In this sense, the thesis not only applies a transdisciplinary approach but also treats it as an explicit object of reflection and as a result.

At the methodological-instrumental level, the research develops three innovative operational frameworks. The geoanthropological framework translates abstract concepts from geoanthropology into analytical tools applicable to concrete industrial contexts, enabling the analysis of sustainability by systematically and rigorously considering complex person-territory-production interactions. The SYMΞX framework creates a management system based on exergy that can be adapted to diverse organizational and sectoral contexts, providing a rigorous physical basis for measuring resource-use efficiency and sustainability. The data-driven SO-LCA methodology proposes a quantitative procedure for social assessment that significantly reduces the subjectivity of previous methods by strategically leveraging advanced statistical techniques, thereby improving comparability and aligning with emerging international standards. Complementarily, the development of synthetic sustainability indices provides comprehensive metrics that capture multidimensionality and interactions, thereby facilitating evaluation, monitoring, communication, and comparison.

At the empirical level, validation in the Italian ceramic district demonstrates the practical feasibility of the proposed frameworks and generates valuable context-specific knowledge for the sector. The identification of sector-specific challenges in the transition toward systemic sustainability, such as energy intensity, raw material consumption, emissions management, and social transformations associated with digitalization, provides concrete guidance for firms and policymakers. Although the specific empirical context is the ceramic sector, many of the findings and tools developed are potentially transferable to other manufacturing sectors facing similar sustainability and complexity challenges, particularly sectors that are energy- and material-intensive and have long historical trajectories.

The fundamental integrative contribution of this doctoral research consists of providing a coherent and comprehensive system of conceptual and methodological frameworks for the operational implementation of systemic sustainability in organizations that also need to maintain high levels of agility in volatile environments, where agility means a dynamic adaptation capability that remains aligned with systemic sustainability goals (Carayannis & Morawska-Jancelewicz, 2022; Dimple & Tripathi, 2024). This integrated system establishes solid conceptual foundations through the geoanthropological perspective, provides a rigorous physical basis through the thermoeconomic SYMΞX framework, develops validated operational tools through the data-driven SO-LCA methodology, addresses the economic, environmental, social, and technological dimensions in an integrated rather than fragmented manner, connects the micro level of the individual organization, the meso level of the industrial district, and the macro level of the supply chain and territory, and offers both diagnostic tools and guidance for continuous improvement and strategic transformation.

This integration responds to the recurrent need in the literature to move beyond fragmented approaches to sustainability, offering instead a systemic and holistic vision that does not remain at an abstract level but provides concrete tools for operationalizing it in real organizational contexts (Srivastava et al., 2022; Villeneuve et al., 2017). The originality of this contribution lies not only in each framework but fundamentally in their synergistic integration into a coherent system that is greater than the sum of its parts. Ultimately, the thesis proposes and demonstrates an applied research program that connects theory, methodology, and practice under the prism of systemic sustainability.

PART II –COMPENDIUM OF PUBLICATIONS

CHAPTER I - SYSTEMIC SUSTAINABILITY AND GEOANTHROPOLOGY

This first article establishes the conceptual foundations of the doctoral research by introducing geoanthropology as an innovative strategic lens for understanding and assessing systemic sustainability in advanced manufacturing contexts. The study adopts a transdisciplinary approach that integrates geoanthropological insights into the analysis of the Italian ceramic industrial district, with a focus on the transition from Industry 5.0 to the emerging concept of Industry 6.0.

The article identifies seven key factors for analysis that span the multiple dimensions of systemic sustainability: resource consumption, production dynamics, innovation, environmental impact, social impact, market dynamics, and economic impact. Through a contingency analysis tailored to the ceramic district's specific characteristics, the study examines how historical events such as shifts in Italian industrial policy, global market slowdowns, and the COVID-19 pandemic have affected the sector in complex and differentiated ways.

The incorporation of geoanthropology provides a transdisciplinary perspective that enables in-depth examination of the complex interactions between people and their environment in industrial contexts. This approach explicitly recognizes the importance of the territorial embeddedness of production systems, moving beyond universalist views that ignore how geographical, cultural, and historical specificities condition sustainability trajectories. The results highlight the central role of innovation, digitalization, and government policies in driving positive changes in production efficiency, market dynamics, and economic impact, while simultaneously revealing persistent challenges in balancing environmental sustainability and resource consumption, as well as in effectively managing the social impacts of digitalization.

The contribution is published in the Global Journal of Flexible Systems Management, an international journal indexed in Scopus and ranked in the first quartile (Q1) in all its categories within Business, Management and Accounting (Business and International Management, Management Information Systems, Strategy and Management, among others). The journal has an SJR indicator of 1.148 and an H-index of 51, reflecting a consolidated trajectory and significant recognition in the fields of management and flexible systems. In addition, it is included in the CABS Academic Journal Guide (AJG 2024) in the field of General Management, Ethics, Gender, and Social Responsibility with a rating of 2, further reinforcing its relevance as an outlet for research in management, sustainability, and organizational governance.

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ORIGINAL RESEARCH

Exploring Systemic Sustainability in Manufacturing: Geoanthropology's Strategic Lens Shaping Industry 6.0

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Abstract *This seminal study explores systemic sustainability within the Industry 5.0 paradigm, using the strategic lens of geoanthropology to shape the emerging concept of Industry 6.0. A transdisciplinary approach is adopted, integrating geoanthropological insights into the analysis of the Italian ceramic district. Seven key factors are considered: resource consumption, production dynamics, innovation, environmental impact, social impact, market dynamics, and economic impact. Historical events such as changes in Italian industrial policy, market slowdowns, and the COVID-19 pandemic are identified as significant for the sector. A contingent analysis tailored to the unique characteristics of the ceramic district provides an in-depth understanding of its challenges and opportunities. The incorporation of geoanthropology provides a transdisciplinary perspective that allows for an in-depth examination of the complex interactions between people and their environment in an industrial setting. The study highlights the central role of innovation, digitalization, and government policies in driving positive changes in production efficiency, market dynamics, and economic impact. Nevertheless, challenges remain, including the delicate balance between environmental sustainability and resource consumption, as well as the effective management of the social impacts of digitization. To address these challenges, a systemic sustainability index derived from geoanthropological insights is proposed as a pragmatic tool to measure and guide the development of sustainability initiatives in the ceramic district. The results of this study not only pave the way for new horizons in sustainability assessment but also provide valuable insights for industrial district managers to formulate strategies that foster organizational flexibility and resilience.*

Keywords Geoanthropology · Industrial district · Industry 5.0 · Industry 6.0 · Manufacturing · Organizational flexibility · Systemic sustainability · Transdisciplinary analysis

JEL Classification O13 · O33 · L61 · J11 · Q56 · Q57

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Introduction

Industrial districts (IDs) offer a valuable lens for investigating how firms generate and share sustainable value within a region-specific area (Sassanelli & Terzi, 2022). IDs are clusters of small- and medium-sized enterprises (SMEs) that specialize in producing business-related goods (Celetti et al., 2023). These SMEs employ a skilled workforce with deep product knowledge, which fosters innovation through learning by doing (Hervas-Oliver et al., 2023a, 2023b). Interdependence between firms in IDs goes beyond business and manufacturing to include a cultural dimension. This cultural dimension contributes to the creation of long-term collaborative relationships based on trust and knowledge sharing (Görmar & Harfst, 2019). One of the strengths of IDs is their ability to balance specialization and flexibility without central coordination. Firms adapt to market demands and promote their competitiveness through local synergies (Hervas-Oliver et al., 2023a, 2023b). Therefore, IDs are not simply agglomerations of firms producing similar goods, but dynamic networks of interactions, knowledge sharing, and mutual support that drive territorial competitiveness and economic growth (Alberti et al., 2021). These unique characteristics of IDs have led scholars to consider the meso-economic level as a distinct set of analytical units between the micro-level of individual firms and the macro-level of the national economy (Sforzi & Boix, 2019). Industrial districts (IDs) are meso-economic spaces where manufacturing activities thrive, facilitating interactions between economic actors (firms and public institutions) and improving the competitiveness of the area (Claver-Cortés et al., 2019). In a supply chain not organized into an ID, individual companies may undertake environmental or social initiatives, but their impact may be limited or undermined by the uncooperative and/or unsustainable behavior of other supply chain actors (Fiorini et al., 2023). Conversely, the collaborative efforts of companies within IDs can create the conditions necessary to promote sustainability in economic, social, and environmental terms (Grodach et al., 2023). Environmentally, IDs adopt green sourcing and production solutions that contribute to the environmental sustainability of the community (Ceglia et al., 2023a). Socially, IDs strengthen social ties and create an integrated and cohesive community (Rocha et al., 2020). Economically, IDs create jobs, strengthen local supply chains, and stimulate regional economic growth (Farinha et al., 2020). Finally, IDs align with the principles of the circular economy, which emphasizes resource efficiency, waste reduction, and product lifetime (Hervas-Oliver & Boix, 2022).

The potential of IDs to promote sustainability in manufacturing and serve as models for sustainable communities (Biancardi et al., 2023) depends on their ability to foster economic growth, social cohesion, environmental stewardship, and resilience within their localities (Ceglia et al., 2023b). Realizing this potential requires an integrated methodological approach that recognizes the inherent diversity among stakeholders and the influential role of contextual factors on sustainability outcomes (Canello & Vidoli, 2022). As the study of manufacturing sustainability expands beyond the traditional boundaries of IDs, a broader understanding of sustainable practices is emerging. While IDs have historically advanced sustainability through collaborative networks and localized synergies, the emergence of systemic sustainability (Pascarella & Bednar, 2022) represents a paradigmatic shift that delves deeper into the intricate interplay of socio-economic and environmental factors within manufacturing environments. Amidst this transformative landscape, concepts such as organizational flexibility (Joseph Jerome et al., 2023) and Industry 5.0 (Barata & Kayser, 2023; Coelho et al., 2023) are gaining prominence, advocating human-centered approaches that integrate cutting-edge technologies such as artificial intelligence, the Internet of Things (IoT), and robotics with human expertise. This integration not only increases production efficiency but also fosters adaptive and agile production processes, thereby enhancing organizational flexibility to meet dynamic market demands (Turner et al., 2023). The convergence of systemic sustainability, organizational flexibility, and Industry 5.0 underscores the need for a comprehensive sustainability framework in manufacturing. By harmonizing these concepts, manufacturing ecosystems can skillfully navigate market volatility while addressing environmental imperatives and fostering social cohesion. This integrated approach recognizes the inherent dynamism of manufacturing systems and underscores the critical role of flexibility and adaptability in addressing evolving challenges (Singh et al., 2021; Srivastava & Bag, 2023; Le & Mohiuddin, 2024). Moreover, flexibility enables companies to adapt quickly and cost-effectively to changes in their environment, technology, organization, and strategy, thereby improving efficiency and organizational performance (D'Adamo et al., 2023). This adaptability promotes stakeholder engagement and facilitates the formation of ecosystems that integrate sustainability and digitalization, in line with the principles of Industry 5.0 (Shukla & Singh, 2023). In Industry 5.0, flexibility allows companies to seamlessly adapt to evolving technological landscapes and organizational structures, fostering innovation, and increasing productivity (Hu et al., 2022; Malaviya & Wadhwa, 2005). This synergy underscores the importance of adaptive and agile approaches to meet dynamic market demands, while advancing sustainability goals (Jiménez-Partearroyo et al., 2023). It also helps in mitigating risks related to economic dimensions and cost control, including regulatory systems and market distortions, such as the alignment of climate policy flexibility mechanisms and the implementation of measures such as the carbon border adjustment mechanism (Barraza de la Paz et al., 2023).

Nevertheless, during this transformative landscape and the emergence of new paradigms, it is critical to acknowledge the significant gaps in our understanding that require attention. First, there is a lack of standardized approaches and tools to measure and evaluate the effectiveness of sustainable practices within the evolving framework of systemic sustainability and the Industry 5.0 paradigm (Vacchi et al., 2024). This deficiency poses challenges for academics and practitioners alike in assessing the impact of initiatives and determining optimal strategies. Second, there is a gap in understanding the practical challenges associated with implementing sustainable practices and integrating concepts such as organizational agility and Industry 5.0 into manufacturing operations. Issues such as organizational change management, employee training, and seamless integration of advanced technologies persist and require innovative solutions (Smuts & Van der Merwe, 2022). Furthermore, a deeper transdisciplinary understanding of the intersection between sustainability, organizational agility, and Industry 5.0 is imperative (Carayannis & Morawska-Jancelewicz, 2022). The integration of knowledge from diverse fields such as engineering, economics, environmental sciences, and social sciences is essential to address the multifaceted challenges in manufacturing (Leng et al., 2022). In addition, the lack of best practices and case studies demonstrating the successful adoption of emerging concepts such as systemic sustainability and organizational agility limits our ability to draw practical lessons from past experiences (Gigauri & Janjua, 2023). There is also an urgent need for a deeper understanding of the long-term impact of sustainable practices and emerging concepts in manufacturing (D'Adamo & Rosa, 2016). This involves assessing the economic, social, and environmental impacts over time, considering changes in the competitive and technological landscape. Finally, recent research has shed light on a significant gap in assessing sustainability performance, particularly within IDs, highlighting the need for a contingent approach to provide scholars and practitioners with actionable insights for crafting effective sustainability strategies and operations (Bressanelli et al., 2022).

The gaps identified in understanding the implementation of sustainable practices within Industry 5.0 call for urgent attention and innovative solutions (Wang et al., 2023). As the industrial landscape shifts toward Industry 6.0, characterized by a broader vision and technological advancements, bridging these knowledge gaps becomes even more imperative to ensure a seamless transition and maximize the benefits of sustainable practices (Bhatti et al., 2021). This emerging paradigm is characterized by a broader and more inclusive vision than previous industrial revolutions, focusing on the use of technology to ensure principles such as the centrality of the consumer and social, environmental, and economic sustainability (Duggal et al., 2022). Industry 6.0, characterized by virtualized production, customer-centric ethics, and a dynamic supply chain, aims to balance human needs with technological challenges. Building on this concept, future scenarios envision emerging technologies revolutionizing production (Damaševičius & Misra (1 C.E.), 2024). Industry 6.0 emphasizes renewable energy, machine independence, interplanetary resource utilization, airborne platforms, anatomical enhancements, and quantum control, presenting significant evolution and new opportunities (Das & Pan, 2022). In this context, the transdisciplinary approach to systemic sustainability in industrial clusters, integrating the principles of Industry 5.0, provides a solid foundation for addressing the challenges and seizing the opportunities of Industry 6.0.

This study seeks to address the gap by adopting a contingency approach to sustainability assessment, originating from the idea of flexible organization in organizational research (Gromoff et al., 2012). This approach aims to provide insights into how contextual factors interact with sustainability outcomes in industrial districts. This innovative perspective can serve as a valuable tool in facilitating the development and implementation of adaptive and context-specific sustainability initiatives, ultimately enhancing the prospects of industrial districts gaining recognition as sustainable communities. To address the gap, this study will focus on four primary research questions:

- *RQ1* In which specific field of knowledge can the contingency approach for the analysis of the sustainability performance of IDs be embedded?
- *RQ2* How does the contingency approach to sustainability enable the design of context-adaptive initiatives in IDSs?
- *RQ3* In the context of Industry 5.0, how can a transdisciplinary approach improve knowledge of the systemic sustainability performance of IDs?
- *RQ4* How does the emerging paradigm of Industry 6.0 intersect with the principles of a transdisciplinary approach and systemic sustainability?

The remainder of the article is organized as follows: "Methodological background" section describes the study context and data source and processing, "Results and discussion" section reports the main results, and "Conclusions" section provides concluding remarks and implications.

Methodological Background

Study Context and Case Focus

To address the knowledge gaps and answer the research questions, a quantitative research approach using an in-depth single-case study design over a while was adopted

(Barbieri et al., 2022). The ceramic tile manufacturing district in Sassuolo, Italy, was selected as the case study for this research (Mattioli, 2019). Located in the province of Modena and the Emilia Romagna region in the north of the country, this district is considered a "hard-to-abate" (HTA) industry due to its high energy and raw material consumption (Rattle et al., 2023). This makes it particularly challenging to achieve significant decarbonization beyond current technology levels. The European Union's ambitious decarbonization targets, which aim to reduce CO_2 emissions by 55% by 2030 (compared to 1990 levels) and achieve carbon neutrality by 2050, further exacerbate this challenge (Bigerna & Polinori, 2022). Despite these obstacles, the ceramics district has gained international recognition for its strict environmental regulations to protect the environment and workers, as well as for its efforts to reduce emissions, recycle industrial water, minimize hazardous substances, and recycle processing waste (Boschi et al., 2023). In this respect, the ceramic district can serve as a model for sustainable industrial communities committed to ecological transition.

Assessing the sustainability performance of industrial districts requires a comprehensive methodology that accounts for the contextual complexities inherent in such assessments. These complexities arise from district-specific variables, including geographic location, production inputs, industrial assets, available technologies, and prevailing public policies, all of which can evolve (Bellandi et al., 2021). A contingency approach (Chavez et al., 2022) can be used to analyze this complex interplay and to understand the role of these factors in improving the efficiency of the industrial system. To illustrate the practical application of this framework, the ceramic district serves as a pertinent example of a "hard-to-abate" industry. This case study allows an examination of the operational achievements and environmental initiatives that underpin the sustainability of the industry.

Data Source

This study aims to address the methodological challenge of collecting data to assess the sustainability performance of the ceramic industry in Italy. To overcome the heterogeneity of the data, a customized dataset was constructed using a variety of sources (Van Den Blink & Steyn, 2018). Production and sales data were collected by consulting the annual reports published by the Italian Association of Ceramic Manufacturers (Confindustria Ceramica, 2023). Annual sectoral financial reports published in aggregate form were used to collect economic and financial data (Bignozzi et al., 2022). By cross-referencing the available data, 24 metrics were identified that are useful for assessing the sustainability performance of the industrial district. The metrics were then grouped into seven main contingency factors that describe the distinctly multidimensional nature of sustainability for this industry. The dataset covers 12 years, from 2010 to 2021, which includes three discontinuity factors: the financial crisis in 2010–2012, the digitization of processes introduced by district companies in 2015–2018, and the impact of the pandemic period in 2020–21. However, the years 2022 and 2023 could not be included due to the different timing of data publication. The units of measurement for the indicators have been adjusted to ensure that they can be interpreted positively by all. In other words, a higher value for each indicator indicates a positive impact. This is evident in the environmental indicators, where the measure is production per unit of emissions, or in the resource consumption indicators, where the measure is production per unit of resources consumed.

This adjustment is necessary for aggregating the indicators into contingency factors and facilitates. Figure 1 shows the framework for analyzing the sustainability performance of an industrial district using different sustainability metrics. The table is divided into two columns: the first column identifies the Contingency Factors, and the second column lists the corresponding Sustainability Metrics. There are seven rows in the table, each representing a different Contingency Factor. These Contingency Factors include Resource Consumption, Production Dynamics, Innovation, Environmental Impacts, Social Impacts, Market Dynamics, and Economic Impacts. Each Contingency Factor is characterized by specific metrics. By providing a comprehensive and multidimensional approach to interpreting an industrial district's sustainability performance, these factors can help identify areas where the industrial district can improve.

The dataset quantifying the performance metrics for each contingency factor over the period 2010–2021 is shown in Fig. 2.

Here's a breakdown of the data set:

1. *Resource consumption* this factor measures how efficiently the district uses resources such as water, energy, and raw materials. Metrics include production per unit of water consumption, production per unit of energy consumption, and production per unit of raw materials consumed.
2. *Manufacturing dynamics* this factor assesses the efficiency and productivity of the manufacturing processes. Metrics include production per employee, production efficiency, and unsold merchandise in stock.
3. *Innovation* this factor measures the district's capacity for innovation and development of new technologies and processes. Metrics include investments in research

CONTINGENCY FACTORS	SUSTAINABILITY METRICS			
RESOURCE CONSUMPTION	Water (m^2/m^3)	Electricity (m^2/kWh)	Natural Gas (m^2/m^3)	/
MANUFACTURING DYNAMICS	Production (m^2)	Production by Employee (m^2/employee)	Production Efficiency (m^2/Ton)	Unsold Merchandise in Stock (mln m^2)
INNOVATION	Investments (€)	Tangible Fixed Assets (€)	/	/
ENVIRONMENTAL IMPACTS	GHG Emissions (m^2/Ton CO_2)	PMP Emissions (m^2/Ton)	VOC_S Emissions (m^2/Ton)	Waste Generation (m^2/Ton)
SOCIAL IMPACTS	Employees (N°)	Average Firm Size (N° Employees)	Turnover by Employee (€)	Share Value by Employee (€)
MARKET DYNAMICS	Total Turnover (€)	Foreign Turnover Ratio (%)	Average Price (€/m^2)	/
ECONOMIC IMPACTS	Goods Expense (€)	Financial Expenses (€)	Net Income (€)	Total Assets (€)

Fig. 1 Analytical framework for assessing the sustainability performance of an industrial district

	RESOURCE CONSUMPTION				MANUFACTURING DYNAMICS				INNOVATION		ENVIRONMENTAL IMPACTS			
	Row Materials Ton	Water m^2/m^3	Electricity m^2/kWh	Natural Gas m^2/m^3	Production m^2	Production by Employee m^2/employee	Production efficiency m^2/Ton	Unsold Merchandise in Stock mln m^2	Investments €	Tangible Fixed Assets €	GHG Emissions m^2/Ton CO_2	PMP Emissions m^2/Ton	VOCs Emissions m^2/Ton	Waste Generation m^2/Ton
2010	7.93E+06	9.26E+01	3.19E-01	3.40E-01	3.87E+08	1.66E+04	4.89E+01	1.93E+02	2.24E+08	2.50E+09	9.52E+01	7.30E+05	2.75E+06	3.41E+02
2011	7.65E+06	9.17E+01	3.32E-01	3.57E-01	4.00E+08	1.80E+04	5.22E+01	1.83E+02	2.48E+08	2.36E+09	1.09E+02	8.85E+05	1.98E+06	3.45E+02
2012	7.24E+06	9.09E+01	3.34E-01	3.46E-01	3.67E+08	1.72E+04	5.07E+01	1.75E+02	2.55E+08	2.31E+09	9.80E+01	8.77E+05	1.59E+06	3.26E+02
2013	7.25E+06	9.17E+01	3.53E-01	3.37E-01	3.63E+08	1.77E+04	5.01E+01	1.52E+02	2.25E+08	2.30E+09	9.71E+01	8.77E+05	1.25E+06	3.41E+02
2014	7.77E+06	9.52E+01	3.66E-01	3.41E-01	3.82E+08	1.96E+04	4.91E+01	1.42E+02	2.86E+08	2.58E+09	9.43E+01	1.02E+06	1.33E+06	3.61E+02
2015	7.88E+06	1.00E+02	2.33E-01	4.18E-01	3.95E+08	2.06E+04	5.01E+01	1.40E+02	3.51E+08	2.73E+09	1.07E+02	1.25E+06	1.30E+06	3.75E+02
2016	8.53E+06	9.71E+01	2.18E-01	3.95E-01	4.16E+08	2.19E+04	4.87E+01	1.41E+02	4.00E+08	2.54E+09	1.16E+02	1.25E+06	1.31E+06	3.48E+02
2017	8.48E+06	9.71E+01	2.25E-01	4.02E-01	4.23E+08	2.17E+04	4.98E+01	1.42E+02	5.15E+08	2.40E+09	1.18E+02	1.26E+06	1.39E+06	3.45E+02
2018	8.49E+06	9.80E+01	2.19E-01	3.95E-01	4.16E+08	2.11E+04	4.89E+01	1.47E+02	5.08E+08	2.50E+09	1.04E+02	1.30E+06	1.26E+06	3.33E+02
2019	8.15E+06	9.80E+01	2.15E-01	3.82E-01	4.01E+08	2.07E+04	4.92E+01	1.41E+02	3.73E+08	2.47E+09	1.01E+02	1.39E+06	1.26E+06	3.06E+02
2020	6.88E+06	9.26E+01	4.17E-01	3.16E-01	3.34E+08	1.78E+04	4.86E+01	9.40E+01	2.03E+08	2.71E+09	9.01E+01	1.38E+06	1.18E+06	3.06E+02
2021	8.81E+06	9.71E+01	4.29E-01	3.24E-01	4.35E+08	2.35E+04	4.94E+01	7.41E+01	3.51E+08	2.73E+09	9.35E+01	1.41E+06	1.32E+06	3.30E+02

	SOCIAL IMPACTS				MARKET DYNAMICS				ECONOMIC IMPACTS			
	Employees N°	Average Firm Size N° Employees	Turnover by Employee €	Share Value by Employee €	Total Turnover mil €	Foreign Turnover Ratio %	Average Price €/m^2	Foreign/Domestic Price Ratio %	Goods Expense €	Financial Expenses €	Net Income €	Total Assets €
2010	2.34E+04	1.72E+02	1.98E+05	1.03E+09	4.63E+09	7.37E-01	1.12E+01	1.20E+00	2.81E+09	2.10E+09	-1.53E+08	3.76E+09
2011	2.22E+04	1.63E+02	2.13E+05	9.68E+08	4.72E+09	7.57E-01	1.14E+01	1.20E+00	2.82E+09	1.90E+09	-8.23E+07	3.26E+09
2012	2.14E+04	1.59E+02	2.15E+05	9.97E+08	4.58E+09	7.99E-01	1.20E+01	1.28E+00	2.99E+09	1.98E+09	-1.04E+07	3.38E+09
2013	2.05E+04	1.56E+02	2.30E+05	1.00E+09	4.73E+09	8.19E-01	1.21E+01	1.29E+00	2.94E+09	1.61E+09	2.84E+08	3.53E+09
2014	1.94E+04	1.50E+02	2.53E+05	1.06E+09	4.91E+09	8.36E-01	1.24E+01	1.32E+00	3.14E+09	1.44E+09	1.32E+08	3.29E+09
2015	1.91E+04	1.50E+02	2.67E+05	1.10E+09	5.12E+09	8.44E-01	1.29E+01	1.37E+00	3.36E+09	1.55E+09	2.48E+08	3.41E+09
2016	1.90E+04	1.47E+02	2.86E+05	1.02E+09	5.42E+09	8.47E-01	1.31E+01	1.38E+00	3.18E+09	1.53E+09	4.31E+08	3.68E+09
2017	1.95E+04	1.45E+02	2.84E+05	9.40E+08	5.55E+09	8.48E-01	1.32E+01	1.38E+00	2.88E+09	1.47E+09	3.52E+08	3.38E+09
2018	1.97E+04	1.37E+02	2.73E+05	9.69E+08	5.38E+09	8.45E-01	1.31E+01	1.37E+00	3.01E+09	1.66E+09	3.02E+08	3.52E+09
2019	1.93E+04	1.35E+02	2.76E+05	9.45E+08	5.34E+09	8.44E-01	1.31E+01	1.40E+00	2.82E+09	1.86E+09	2.22E+08	3.69E+09
2020	1.87E+04	1.33E+02	2.74E+05	8.57E+08	5.13E+09	8.60E-01	1.31E+01	1.41E+00	2.46E+09	1.98E+09	1.82E+08	4.29E+09
2021	1.85E+04	1.31E+02	3.33E+05	9.55E+08	6.17E+09	8.43E-01	1.35E+01	1.35E+00	3.50E+09	1.96E+09	2.91E+08	4.47E+09

Fig. 2 Data set and overview of the key metrics used to assess the sustainability performance of the Italian ceramic tile district

and development, number of patents filed, and new product introductions.

4. *Environmental impacts* this factor assesses the district's impact on the environment, such as air and water pollution and greenhouse gas emissions. Metrics include greenhouse gas emissions per unit of production, particulate matter emissions per unit of production, and VOC emissions per unit of production.
5. *Social impacts* this factor assesses the district's impact on the local community, such as employment, wages, and working conditions. Metrics include number of employees, employee turnover rate, and average wage.
6. *Market dynamics* this factor assesses the district's competitiveness and position in the market. Metrics include foreign turnover ratio, average price, and export/domestic sales ratio.
7. *Economic impacts* this factor assesses the district's financial performance and contribution to the local economy. Metrics include financial expenses, net income, and total assets.

This data set is the basis for the statistical analysis that follows.

Data Processing

To comprehensively assess the evolution of sustainability in the industrial district, we employ a data-driven methodology that is particularly relevant in the systemic context of Industry 5.0. This approach integrates advanced technologies and data analytics to improve decision-making processes by facilitating the analysis and visualization of complex data sets. Our method begins by identifying and analyzing seven contingency factors that influence the sustainability of industrial districts, observing their evolution and interrelationships over time.

The methodology consists of two main phases: quantification and data scaling. In the quantification phase, weights are assigned to each indicator according to its importance within its contingency factor, to aggregate these weighted indicators into an overall sustainability index. Since the importance of each factor (criteria) significantly impacts the final decision, researchers have created various methods to assign weights to these factors (Mishra et al., 2023). This is followed by the scaling phase, where data corresponding to each factor are normalized to maintain its relevance and allow its aggregation from the weights calculated above. The result is an index that serves as an overall Key Performance Indicator (KPI), providing a systemic view of the industrial district's sustainability performance and supporting strategic decisions.

Starting the data processing, the first step is the weighting of the indicators to aggregate them into their corresponding contingency factor. This task is performed through dimensionality reduction techniques, combining the original indicators into indexes that represent their behavior comprehensively. To follow a purely data-driven method of weighting and aggregating indicators, Principal Component Analysis (PCA) will be employed as an effective statistical technique for simplifying databases while keeping the overall nature of the original data (Ayadi et al., 2024). The PCA method aggregates the original variables by creating orthogonal vectors or Principal Components, assigning coefficients to each indicator according to its variability relative to the rest. Based on the PCA method, we create an indicator aggregation model considering these considerations:

- We consider variability as the relative information contributed by each variable, and therefore, each principal component (PC) represents the aggregation of indicators according to the information contributed by each one in that component (Mohsine et al., 2023).
- By calculating the first principal component (PC1) on the indicators of each contingency factor, the indicators aggregation formula is obtained according to the information provided relative to the vector representing the contingency factor.
- The indicators are selected based on their direct impact on their contingency factor. The remaining principal components of the PCA are orthogonal to PC1, representing the information of the indicators that do not directly impact their contingency factor.

Based on these considerations, the R code of the model is created to obtain the aggregation values of the indicators or weights, using the "prcomp" command as the key package to operate the PCA. First, we divide the database into different contingency factors, to be able to apply a PCA for each of them. Then, the PCA-based indicator aggregation process is performed, which consists of three steps as shown in Table 1. First, PC1 is calculated on the indicators of a contingency factor. The second stage consists of getting the polynomial representation of PC1, with the coefficients corresponding to each indicator. When adding values, the weights must be positive and add up to unity, so the third step consists of dividing the absolute value of each coefficient by the sum of the absolute values of all the coefficients.

Then we move on to the normalization of the indicators, following a data-driven model that is robust and integrable in the information system of an industrial district. In this case, we employ sigmoid normalization to scale and compare indicator values due to their characteristics that fit perfectly with our case study. Sigmoid standardization combines two important data preprocessing techniques: normalization (also known as z-score normalization) and sigmoid transformation. Normalization and sigmoid transformation together form a powerful preprocessing method for data analysis and machine learning, where standardization rescales data to have a mean of 0 and a standard deviation of 1, improving comparability across features. The subsequent sigmoid transformation maps these standardized values to a bounded (0, 1) range, improving the interpretability of the data in each interval. The formula for this combined approach is:

$$x_s = \frac{1}{1 + e^{\left(\frac{x-\mu}{\sigma}\right)}}$$

where x is the input value to be standardized and transformed. μ is the mean of the dataset, which helps center the data around 0. σ is the standard deviation of the dataset, which scales the data so that it has unit variance. x_s represents the sigmoid function applied to the standardized value of x.

This methodological approach remains relatively unexplored in data analysis, as reflected by the lack of studies in the literature (Liang & Ren, 2022; Wang et al., 2018). In our study, sigmoid standardization is preferred over max–

Table 1 Principal component analysis process applied to sustainable index definition

Step 1: Calculating the first principal component (PC1)
Given a set of social indicators $X = [x_1, x_2, \ldots, x_n]$ where each x_i represents an indicator and n is the total number of indicators, PCA transforms this set into principal components
The first principal component (PC1) is calculated by finding the vector of coefficients $a = [a_1, a_2, \ldots, a_n]$ that maximizes the variance of X projected onto a subject to $\|a\| = 1$. This can be formulated as the optimization problem:
$\max_a Var(Xa)$ subject to $\|a\|^2 = 1$
Step 2: Representation of PC1
PC1 is represented as the weighted sum of the original indicators by their coefficients:
$PC1 = a_1x_1 + a_2x_2 + \ldots + a_nx_n$
This can be expressed in matrix form as $PC1 = Xa$.
Step 3: Weighting the coefficients
To ensure the coefficients are positive and sum to one, we perform a normalization:
$a'_i = \frac{\|a_i\|}{\sum_1^n \|a_k\|}$
This transforms each a_i coefficient into a weight a'_i for the corresponding indicator, ensuring all weights are positive and their sum equals 1

min standardization because it handles outliers more efficiently by compressing all values into an interval (0, 1) by taking the extreme data as a reference without distorting the distribution.

Finally, the value of the contingency factor is obtained by the polynomic formula shown below, adding the product of each scaled indicator by its weight.

$$C.\text{Factor}_j = \sum_{i=1}^{n} a'_i x_{si}$$

where x_{si} corresponds to the i indicator value standardized. a'_i corresponds to the weight for the corresponding indicator i. $C.\text{Factor}_j$ corresponds to the index value for each contingency factor.

This methodology maximizes the retention of critical information by systematically integrating diverse indicators into a contingency factor. This objective and methodical approach ensures the generation of meaningful results that are crucial for assessing the sustainability of industrial districts. Notably, this method offers substantial improvements over more subjective approaches, providing enhanced objectivity, robustness, flexibility, and adaptability across various contexts. These attributes, documented extensively in the literature (Abdella et al., 2020; Beiragh et al., 2020; Reisi et al., 2014), establish our methodology as a superior tool for facilitating precise and strategic decision-making in the evolving landscape of Industry 5.0.

Results and Discussion

Knowledge Framework

The multidimensional contingency factor approach to assessing the sustainability of industrial districts requires an innovative analytical framework to provide a transformative interpretation of sustainability. Such a framework must be based on solid theoretical foundations, represented in this study by systemic sustainability and geoanthropology. Systemic sustainability, as an innovative paradigm, requires an analytical approach that goes beyond simple post-reporting to provide a transformative measurement that considers the interconnections and interdependencies among the elements of the system (Mouthaan et al., 2023). Similarly, geoanthropology constitutes a transdisciplinary conceptual basis for analyzing sustainability in industrial settings, providing an integrated perspective for understanding the complex interactions between humans and their natural and social environments (Bätzing, 2023).

Before laying the foundation for the multidimensional analytical framework, however, it is essential to provide a clear definition of the concepts of "*systemic sustainability*" and "*geoanthropology*," starting with the etymological meaning of the words themselves. Sustainability comes from the Latin word "*sustentare*," meaning "to support" or "to maintain," indicating the ability to maintain a state or equilibrium over time (Vargas-Hernández et al., 2021). Systemic comes from "*system*," which in turn comes from the Greek "*systēma*" (σύστημα), meaning "set of interconnected parts (Löbler, 2016). Thus, systemic sustainability refers to the ability to maintain the equilibrium and harmonious functioning of a complex system over the long term, considering the interconnectedness and interdependence of its components. Regarding geoanthropology, "geo" is derived from the Greek "*ge*" meaning "Earth," and "anthropology" is derived from "*anthropos*" (man) and "*logos*" (study), indicating the interdisciplinary study of the interactions between humans and their natural environment, with a focus on geographic, ecological, cultural, and social aspects (Rispoli, 2022).

The concept of systemic sustainability is based on the idea that any complex system, such as a business or an ecosystem, is made up of multiple interrelated and interacting elements. These systems include not only environmental and economic aspects but also social and cultural dimensions (Sztangret, 2020). Geoanthropology provides a theoretical and methodological framework for understanding these complex interactions by examining how humans relate to their natural and social environments (Renn, 2021). Based on deductive inferences from existing literature, it can be concluded that geoanthropology plays a central role in systemic sustainability by elucidating the linkages between human activities and their lasting environmental and social impacts. This comprehensive approach facilitates the formulation of sustainability strategies that consider the intricate interplay between environmental, social, and economic factors within a system, thereby promoting a sustainable and harmonious equilibrium. The theoretical and methodological foundations of systemic sustainability, which emphasize the interconnectedness of complex systems across environmental, economic, social, and cultural domains, are firmly grounded in geoanthropology. As an emerging scientific field, geoanthropology offers a holistic perspective on human–environment interactions, incorporating geophysical, ecological, anthropological, and socio-economic dimensions within a transdisciplinary and systems framework.

Geoanthropology can be considered a field of knowledge because it takes into a holistic view the interactions between the geophysical and environmental dimensions and the anthropological and socio-economic dimensions of a complex system (Barker & Barker, 1988). Geoanthropology is an emerging scientific discipline dedicated to the study of the complex relationships between humans and their environment, encompassing the interactions between natural and socio-economic capital (Renn, 2022). The discipline draws on a wide range of analytical methodologies from the natural, social, and engineering sciences, all integrated within the overarching framework of geoscience and anthropology. Two fundamental characteristics are central to defining the discipline: first, a transdisciplinary approach that generates a comprehensive perspective on human–environment interactions, and second, a systemic perspective that recognizes these interactions as integral components of a complex and interrelated system (Bätzing, 2023).

The systemic view of geoanthropology is equally applicable to the study of manufacturing organizations, providing a comprehensive framework for assessing the interactions between individuals, the geographic context, and production processes. Within this framework, geoanthropology can examine the interrelationships between natural resources, the actors involved in production processes, and other complex systems. Emphasis is placed on the role of natural resources in shaping production dynamics, the social and economic interactions associated with production, and the complex interactions between production processes and various other factors, including geopolitics, regulatory frameworks, and industrial policies. If we think of geoanthropology as a new discipline that studies human interaction with the planet, its object of study is the technosphere (Renn, 2022). The technosphere, a defining concept in geoanthropology, encompasses the complex network of human-made technologies and infrastructures that form an interdependent system interacting with Earth's spheres, including the lithosphere, atmosphere, hydrosphere, and biosphere. The technosphere exerts profound environmental and socio-economic impacts while serving as an enabler of human capabilities, fostering growth and prosperity. However, it is critical to recognize that the technosphere also imposes constraints, as exemplified by climate change (Picot & Guillaume, 2023).

Figure 3 presents the transdisciplinary approach of this study, based on the geoanthropological framework proposed by the Max Planck Institute for the History of Science. Four interpretive perspectives, focusing on Time, Life, Society, and Earth, explore the transformative dynamics of the diachronic and synchronic relationship between humanity and the planet in the Anthropocene (Barker & Barker, 1988). These perspectives are intertwined in a transitional space between the "hard sciences" and the "soft sciences": the technosphere (Pipere & Lorenzi, 2021). Within the four interpretive domains are identified the seven contingency factors already described in Figs. 1 and 2, while at the center of the diagram is the technosphere as the space where systemic cross-interaction occurs between human activity and the planet in the past, present, and future. The sustainability assessment model adopted in this study is based precisely on quantifying the systemic interactions of the contingency factors.

Furthermore, geoanthropology's systems perspective extends to production organizations, providing a framework for assessing the interactions between individuals, the environment, and production processes. Within this framework, geoanthropology explores the interrelationships between natural resources, production processes, and

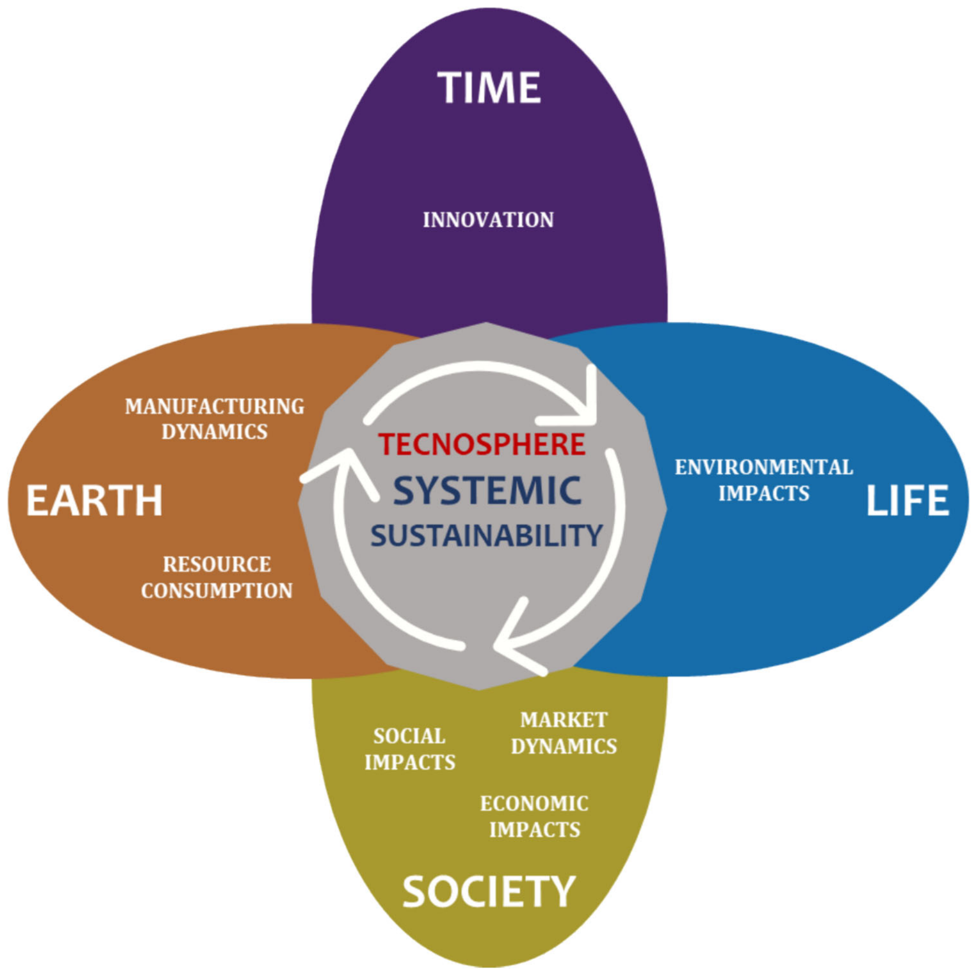


Fig. 3 Geoanthropological framework of contingency factors [Based on the model proposed by the Max Planck Institute for the History of Science (MPIWG)]

external factors such as geopolitics and regulations. If we view geoanthropology as the study of human interaction with the planet, the technosphere emerges as a focal point—a network of human-made technologies interacting with the earth's spheres. Here, systemic sustainability is assessed, and Industry 5.0 practices are implemented, representing the convergence of human activity and the planet. The conceptual framework proposed in Fig. 4 represents an innovative approach that integrates key concepts from systemic sustainability, geoanthropology, and Industry 5.0 and provides a detailed roadmap to guide the transformation to more sustainable industrial practices.

This approach is significant because it recognizes and addresses the complex interactions between human activities and the natural environment, moving beyond traditional sectoral approaches that often ignore these relationships. The four interpretive perspectives—Time, Life, Society, and Earth—each emphasize the importance of considering historical context, ecological balance, social dynamics, and securing resources for the future. These perspectives provide a basic conceptual framework for fully understanding the complexity of systemic sustainability and for directing action toward goals of equity and environmental sustainability. In addition, the framework identifies seven key contingency factors, such as resource use and impacts, market changes, and innovation, that must be carefully evaluated to ensure long-term sustainability. In parallel, the adoption of the Industry 5.0 principles of humanity at the center, decentralization, and co-creation are an important step toward building a more sustainable, human-centered industrial model. These principles incentivize active individual participation, organizational flexibility, and stakeholder collaboration, promoting a more inclusive and sustainability-oriented vision for the future of the industry.

Data Analysis

This section presents the analysis of data from the Italian ceramic industry to understand its evolution and sustainability, as well as the mutual influence between a set of key indicators selected through a multidisciplinary approach. The analysis is based on a data set of 24 metrics collected from 2010 to 2021. These indicators have been grouped

ELEMENT	DESCRIPTION	ROLE IN ACHIEVING SYSTEMIC SUSTAINABILITY
CENTRAL ELEMENT	**Technosphere**	**Represents the interconnectedness of human-made infrastructure and earth's natural spheres**
Four Interpretive Perspectives		
1.Time	Timeline extending from the past to the future	Emphasizes historical context and future projections for sustainability.
2.Life	Stylized representation of an ecosystem	Highlights the impact of human activities on biodiversity.
3.Society	Network of interconnected people	Emphasizes the social dimension of sustainability.
4.Earth	Globe with landmasses, oceans, and atmosphere	Signifies the overall environmental impact of human activities.
Seven Contingency Factors		
1.Resource Consumption	Flow chart depicting resource extraction, processing, and waste generation	Indicates the impact of resource consumption on sustainability.
2.Production Dynamics	Stylized factory with interconnected components	Represents the efficiency and environmental footprint of production processes.
3.Innovation	Lightbulb symbolizing new ideas	Signifies the role of innovation in driving sustainable solutions.
4.Environmental Impact	Pollution cloud hovering above the technosphere	Indicates the negative environmental consequences of human activities.
5.Social Impact	Diverse group of people interacting	Represents the social implications of industrial activities.
6.Market Dynamics	Graph showing supply and demand curves	Illustrates the economic dynamics of the district.
7.Economic Impact	Stack of coins	Signifies the financial performance and economic well-being of the district.
Eight Practices for Industry 5.0		**Core Tenets of Industry 5.0**
1.Human-Centricity	Human collaboration with technology at the forefront	Emphasizes the role of human expertise, creativity, and decision-making in Industry 5.0.
2.Sustainability	Environmental responsibility and resource optimization embedded in production processes	Integrates sustainability as a central pillar of Industry 5.0, moving beyond Industry 4.0's focus on automation and efficiency.
3.Resilience	Ability to adapt to disruptions and changing circumstances	Promotes the development of agile and adaptable systems that can withstand challenges and maintain sustainability.
4.Organizational Flexibility	Adaptability to changing market demands, technologies, and environmental conditions	Enables organizations to adjust their structure, processes, and strategies to remain competitive and sustainable in the dynamic Industry 5.0 landscape.
5.Data-Driven Decision-Making	Leveraging real-time data for optimization and insights	Utilizes data analytics to enhance efficiency, resource management, and sustainability performance.
6.Decentralization	Distributed decision-making and autonomous systems	Empowers individuals and local communities to make informed decisions and contribute to sustainability initiatives.
7.Hyper-Personalization	Tailored products and services based on individual needs and preferences	Enables mass customization and personalized experiences, catering to diverse consumer demands.
8.Co-Creation	Collaboration between stakeholders to generate value	Fosters collaboration among businesses, customers, research institutions, and other stakeholders to drive innovation and sustainability.

Fig. 4 Comprehensive framework for systemic sustainability in industrial districts, integrating geoanthropology and Industry 5.0

into seven main categories known as contingency factors: resource consumption, production dynamics, innovation initiatives, environmental impact, social impact, market dynamics, and overall economic impact.

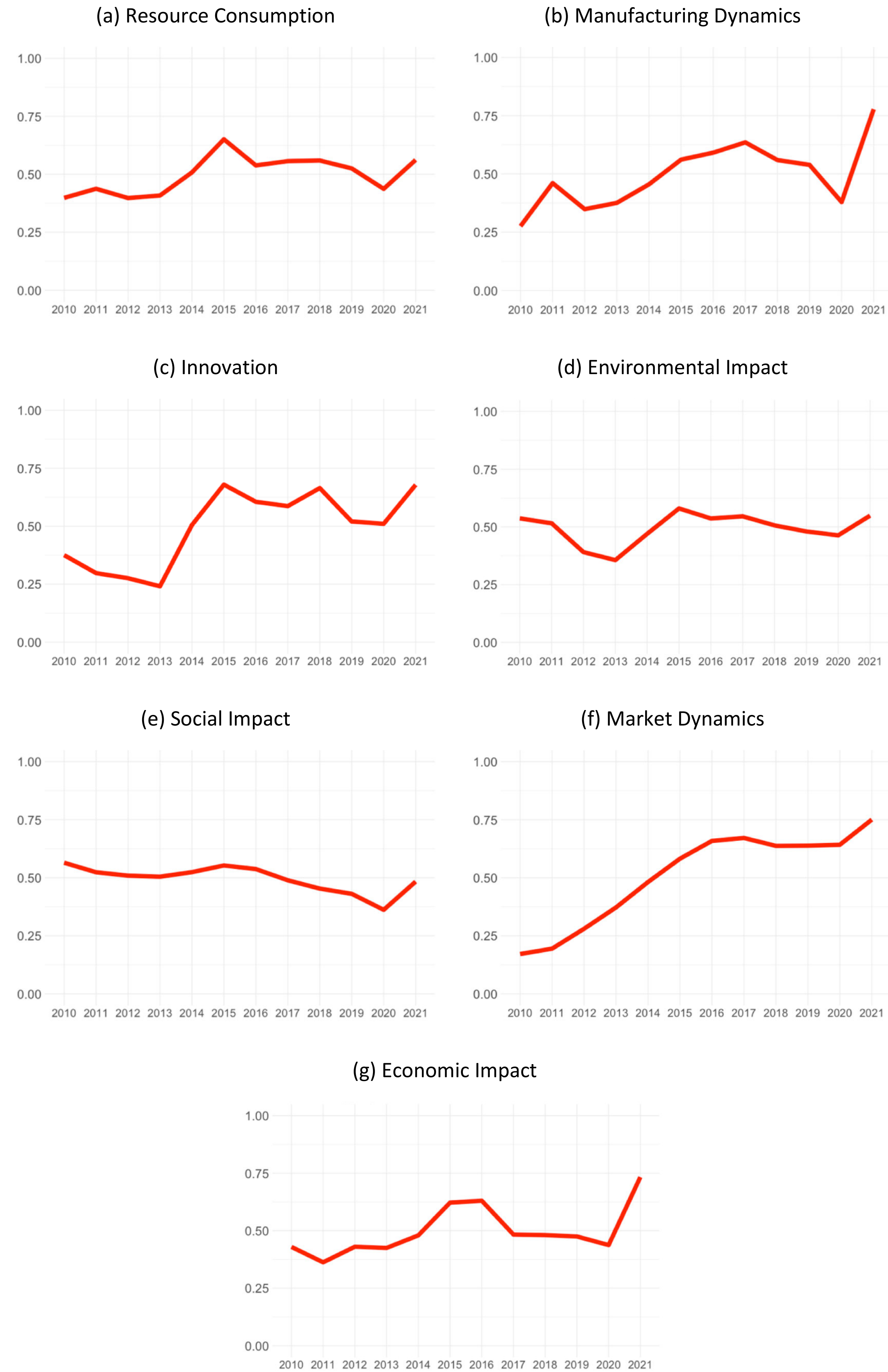
The analysis of these data was done objectively by assigning each indicator a weight proportional to its contribution to the overall set of information. These weights were calculated using the coefficients obtained from Principal Component Analysis (PCA) for each contingency factor. This method made it possible to synthesize the data of 24 individual variables into a more practical set of 7 aggregated variables, allowing a clearer analysis of the evolution of the ceramics sector. The study of the sustainability of the district is based solely on the analysis of internal sector data, without the inclusion of external values. This ensures that the contingency factors accurately reflect the specific characteristics and behaviors of the sector in question. In addition, the implementation of standardization using the sigmoid function mitigates the effect of outliers, ensuring that the interpretation of the results is robust and representative of general trends, without being distorted by extreme values.

However, it is important to recognize that this approach requires that time series be interpreted based on their internal patterns and trends, rather than as absolute values comparable to other sectors or external standards. Therefore, the assessment of sustainability in this context focuses on identifying relative improvements and areas of opportunity within the sector itself, promoting a deep and specific understanding of its sustainability challenges and achievements. The next step is the analysis of the time series, as shown in Figs. 5 and 8. This phase includes the seven contingency factors, the four domains of geoanthropology, and the holistic indicator of systemic sustainability. Emphasis is placed on the trajectory of each time series, identifying dominant trends and key events, as well as the correlation between them. This analysis aims to understand the evolution of the sector in recent years and provide insights that illuminate its future direction.

Developing Contingency Indicators

The research on the Italian industrial ceramic district has focused on a detailed analysis of the time series of the seven contingency factors shown in Fig. 3. These factors have been significantly influenced by three historical events.

The Italian government's industrial policy, which between 2014 and 2015 spurred investments to modernize production facilities and implement digital technologies in line with Industry 4.0; a market slowdown with a reduction in demand starting in 2016; and the COVID-19 pandemic in 2020 shocked global markets. These events are critical to understanding the variability of each factor. Resource


(a) Resource Consumption
(b) Manufacturing Dynamics
(c) Innovation
(d) Environmental Impact
(e) Social Impact
(f) Market Dynamics
(g) Economic Impact
0.00
0.25
0.50
0.75
1.00
2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021

◀ **Fig. 5** Trends over time of the seven contingency factors and the sustainability index

consumption (Fig. 5a) shows a stable trend with a slight positive inclination, interrupted by a peak and valley attributable to R&D investment, the fall in demand, and the pandemic. In manufacturing dynamics (Fig. 5b), a generally intermittent improvement is observed, interrupted in 2020 but with increases in production and efficiency indicators. Innovation (Fig. 5c), measured through investment in digitization and fixed assets, showed a notable increase in 2015, aligned with digital transformation and post-COVID-19 recovery. Environmental impact (Fig. 5d), though stable, reflects in its indicators a move toward cleaner and more efficient production. Social impact (Fig. 5e) is marked by the market slowdown in 2016. There is stability with a negative trend in the volume of companies and employees, although with improvements in the quality of human capital, demonstrating the duality of digitization: It increases the value per employee but reduces the total number of workers. Market dynamics (Fig. 5f) stand out for their positive trend despite the market slowdown, due to the sector's commitment to internationalization and digitization, which is reflected in a substantial increase in total billings. Lastly, economic impact (Fig. 5g), although slightly positive, has been marked by significant investments in digitization and post-pandemic recovery efforts.

Therefore, the digitalization process has played a crucial role in the evolution of the industrial district, with a significant impact on production, the market, and the social fabric, as well as the resilience of the sector to the market slowdown and the impact of COVID-19. Government incentives, along with internationalization strategies, have contributed significantly to increasing the competitiveness of companies, as evidenced by the positive trends observed in market dynamics and economic impact. It is important to note, however, that although productive efficiency has increased, this improvement has not directly translated into greater efficiency in resource consumption or environmental impact. In the social sphere, digitization has had a positive impact on the quality of human capital, but this has been accompanied by a reduction in the total number of employees and enterprises.

Developing Geoanthropology Domains

The seven individually analyzed contingency factors are now integrated into the holistic theoretical framework of geoanthropology. This approach, rooted in anthropology, advocates a holistic study of sustainability that integrates the analysis of various scientific disciplines into four main domains: Time, Earth, Life, and Society. The Time domain encompasses the history and evolution of both humans and the planet, reflected here through innovation and time series analysis. Earth focuses on the geological sciences and is represented here by the consumption of natural resources and the dynamics of production. Life encompasses the biological sciences, explored in our study through environmental impacts. Finally, Society encompasses the social and economic sciences, analyzed in our research through social impact, market dynamics, and economic impact.

Examining the time series of each domain (Fig. 8), we observe patterns and trends consistent with the contingency factors analyzed. In particular, the Time domain (Fig. 8a), represented by the Innovation factor, shows a significant jump coinciding with the process of digitization of the industrial district. On the other hand, the Life domain (Fig. 8d) shows a stable and slightly positive trend, corresponding to the Environmental Impact factor. The Society domain (Fig. 8b) stands out for its pronounced positive trend, driven by digitization and interrupted only by the impact of COVID-19. Meanwhile, the Earth domain (Fig. 8c) shows a similar pattern, but with a much more moderate trend.

The correlation matrix in Fig. 6 illustrates the relationships among the four domains, using red hues to indicate high correlation pairs and blue hues for medium correlation pairs. Generally, there is a strong correlation across all domains. The Time domain demonstrates a significant relationship with others, most notably with Society, underscoring the profound influence of innovation across all study indicators. Additionally, the correlation between Earth and Society is evident, reflecting the industrial district's ability to generate social value while enhancing production efficiency and reducing resource use. The Life domain exhibits the lowest correlation, indicating that environmental impacts had minimal effects on the other

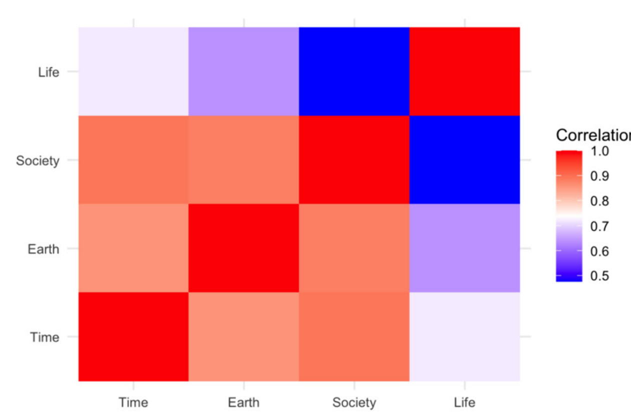


Fig. 6 Correlation matrix of geoanthropology domains

domains during the study period from 2010 to 2021. This period did not provide sufficient data to assess the impact of decarbonization efforts fully. This high level of correlation among the domains underscores the paradoxical nature of sustainability, achieved through a balanced interplay rather than individual domain development.

To visualize the evolution of geoanthropology domains over time, a spider web graph model (Fig. 7) is employed to represent the values for the years 2010 and 2021. This approach facilitates the simultaneous comparison of trends across multiple domains (Earth, Time, Society, and Life) on a single 2D plane. As evident, the domains of Earth, Time, and Society all exhibit a clear upward trend between 2010 and 2021. This suggests an increase in economic and social value, potentially linked to factors such as innovation and improved natural resource management. Conversely, the value for Life remains relatively stable throughout the analyzed period. This stability might indicate that there have been no significant changes in energy resource management practices during this timeframe.

Finally, digitalization has emerged as a powerful driver of change, especially in the social domain, but its interaction with environmental sustainability seems less direct. The resilience and adaptability of the domains to disruptive events such as the COVID-19 pandemic highlight the importance of integrated strategies that strengthen sustainability in all its facets and prepare the industrial ceramics district for future challenges.

Developing Systemic Sustainability Index

Finally, the four geoanthropological domains are combined to formulate a systemic sustainability index. Examining the evolution of the index over time (Fig. 8e) reveals the same tendencies and patterns previously identified in the contingency factors and geoanthropological domains. There is a general slightly positive trend over time, as well as a pronounced peak and trough, reflecting the digitization process and the impact of the COVID-19 pandemic, respectively. This comprehensive index accurately reflects the general evolution of the industrial district throughout the period analyzed from its 24 metrics, indicating that the methodology of analysis and aggregation of elements implemented for this study is appropriate and effective. The comprehensive analysis of the Italian ceramic industry, focusing on seven contingency factors and four geoanthropological areas, highlights the effectiveness of our methodological approach in understanding the evolution and sustainability of the sector. Innovation, promoted by the Italian government's industrial policy between 2014 and 2015, has played a crucial role in positively influencing factors such as production efficiency, market dynamics, economic impact, and social impact, despite the reduction in the number of companies and employees. The resilience to the market slowdown and the COVID-19 pandemic is particularly noteworthy, highlighting the high level of resilience of the sector. The creation of a holistic systemic sustainability index that reflects the patterns of contingency factors confirms the validity of our approach, showing a generally slightly positive trend and highlighting the role of innovation and the sector's adaptability to major challenges. This comprehensive approach not only sheds light on the evolution of the Italian industrial ceramics district but also underlines the importance of multidisciplinary strategies to strengthen sustainability and prepare the sector for future challenges.

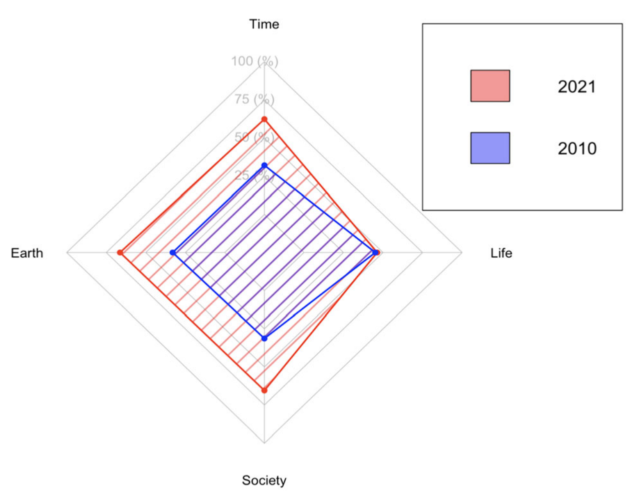


Fig. 7 Spider Web Graph trends in geoanthropology domains between 2010 and 2021

Improving Organizational Flexibility

The proposed methodological approach, using contingency factors and a geoanthropological lens, proves to be a valuable tool for organizations in the ceramic district to improve their flexibility in several dimensions: strategy, structure, systems, people, and culture.

Strategic flexibility contingency factor analysis enables organizations to identify trends and anticipate emerging challenges, thereby informing strategic adjustments in advance. For example, the observed impact of digitization on market dynamics highlights the need for strategic investments in further digital transformation to maintain competitiveness.

Structural flexibility by understanding how different domains (Time, Earth, Life, and Society) interact within the geoanthropological framework, organizations can identify areas where structural changes are needed to improve adaptability. For example, the observed stability

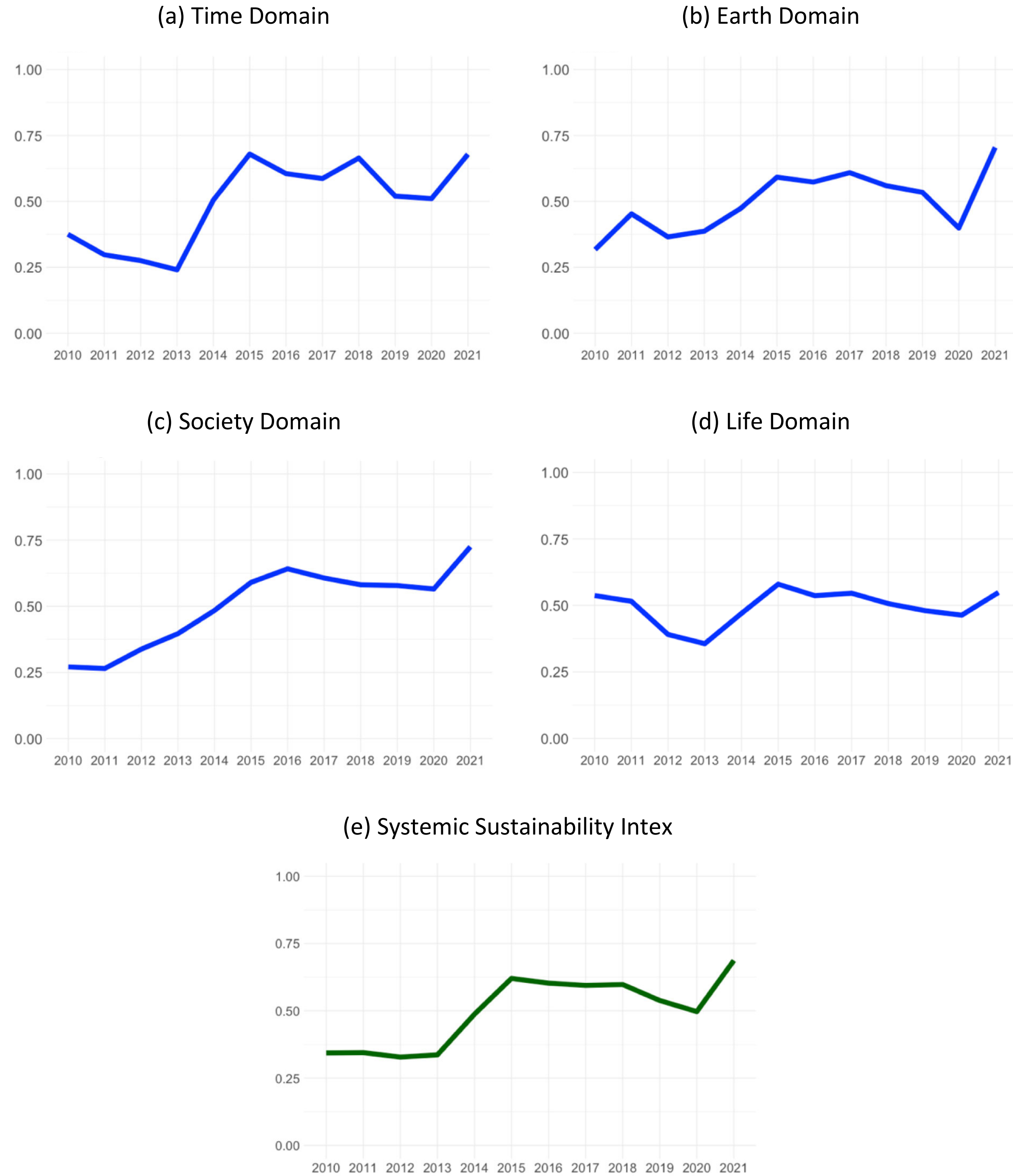


Fig. 8 Trends over time of the four domains of Geoanthropology and the systemic sustainability index

of resource consumption despite increasing production efficiency suggests the need for structural changes to promote circular economy practices.

Systemic flexibility the methodology facilitates the assessment of the adaptability of existing systems to changing circumstances. For example, recognizing the limited influence of environmental impacts on other areas could lead to the development of more integrated systems that address environmental issues along with other aspects of sustainability.

Flexibility of people and culture analysis sheds light on the social impact of change, such as the reduction in the workforce due to digitalization. This awareness enables organizations to develop flexible human resource policies and cultivate a culture of lifelong learning to facilitate workforce adaptation.

By integrating the proposed methodology into their operations, organizations within the ceramic district can cultivate a culture of continuous improvement, enabling them to thrive in a rapidly changing and uncertain environment. This enhanced agility will enable them to meet future challenges, capitalize on emerging opportunities, and ultimately achieve long-term success. Finally, the proposed methodology aligns seamlessly with the SAP-LAP framework (Situation, Actor, Process, Learning, Action, Performance) (Singh et al., 2023), which was first pioneered by Sushil (2001). It begins by analyzing the situation through the contingency factors and geoanthropological domains and then identifies the key actors within the organization. By understanding the processes involved and the learning that takes place, the framework guides the development of actions that lead to improved performance and, ultimately, increased organizational agility.

The diagram in Fig. 9 represents a conceptual model for systemic sustainability assessment applied to the case of the Italian ceramic industrial district. It is based on the SAP-LAP (Situation–Actor–Process–Learning–Action–Performance) framework and integrates the geoanthropological lens for a more in-depth and multidimensional analysis that can guide the development of concrete actions to improve the district's flexibility and performance. The arrows in the diagram indicate the flow of information and relationships between various components of the framework.

Industry 6.0: A Symbiotic Future Driven by Geoanthropology and Systemic Sustainability

While the term Industry 6.0 is not widely established or formally defined, it is emerging as the next frontier of industrial transformation beyond Industry 5.0, which emphasizes human centricity, sustainability, and collaboration in manufacturing processes. Industry 6.0, on the other hand, is expected to delve deeper into human augmentation, hyper-intelligence, and human–machine symbiosis. In Industry 5.0, the focus is on human–machine collaboration, using technology to augment human capabilities. In contrast, Industry 6.0 represents a transition to human–machine symbiosis, where humans and machines combine their strengths to achieve higher levels of intelligence and performance. While Industry 5.0 focuses on sustainability and environmental responsibility, Industry 6.0 has the potential to address global challenges such as climate change and resource scarcity through advanced technologies. Industry 5.0 focuses primarily on manufacturing processes, while Industry 6.0 is envisioned to encompass broader aspects of society, including healthcare, education, and urban planning. While Industry 5.0 is still in its early stages of development, Industry 6.0 represents a glimpse into the future of industrial transformation, where humans and machines work in synergy, augmented by cutting-edge technologies, to shape a more sustainable, intelligent, and connected world. It is important to note that Industry 6.0 is still a theoretical concept, and its specific technologies and applications have yet to be fully defined. However, it represents the ongoing evolution of manufacturing toward a future where humans and machines work more closely together, supported by advanced technologies, to achieve even higher levels of productivity, sustainability, and well-being.

Table 2 represents a prospective focus for Industry 6.0, highlighting the critical role of geoanthropology and systemic sustainability in creating an innovative and sustainable industrial future that is responsive to human needs. Geoanthropology provides a deep understanding of the complex dynamics between humans and their environment, informing the development of technologies and industrial practices that are sensitive to socio-environmental interactions. At the same time, systemic sustainability provides a robust conceptual framework for balancing economic, social, and environmental goals, promoting the design of resilient industrial solutions guided by circular economy principles. The synergistic integration of these disciplines creates a powerful framework for the design and implementation of human-centered and sustainable industrial technologies. This approach promotes sustainable innovation by developing solutions that not only optimize operational efficiency but also address human needs and contribute to resource conservation and reduced environmental impact. In addition, attention to ethics in the implementation of advanced industrial solutions is critical to ensure that technological developments are ethically responsible and respectful of fundamental human values.

This transdisciplinary approach reflects a deep understanding of the interrelationships between human, environmental, and social issues and provides valuable guidance for navigating Industry 6.0 toward a sustainable, human-centered future. The transdisciplinary framework in Table 2, by integrating geoanthropology and systemic sustainability, provides a valuable lens for understanding and shaping the emerging concept of Industry 6.0. By embracing these perspectives, Industry 6.0 can become a transformative force for sustainable development, addressing global challenges and improving human well-being.

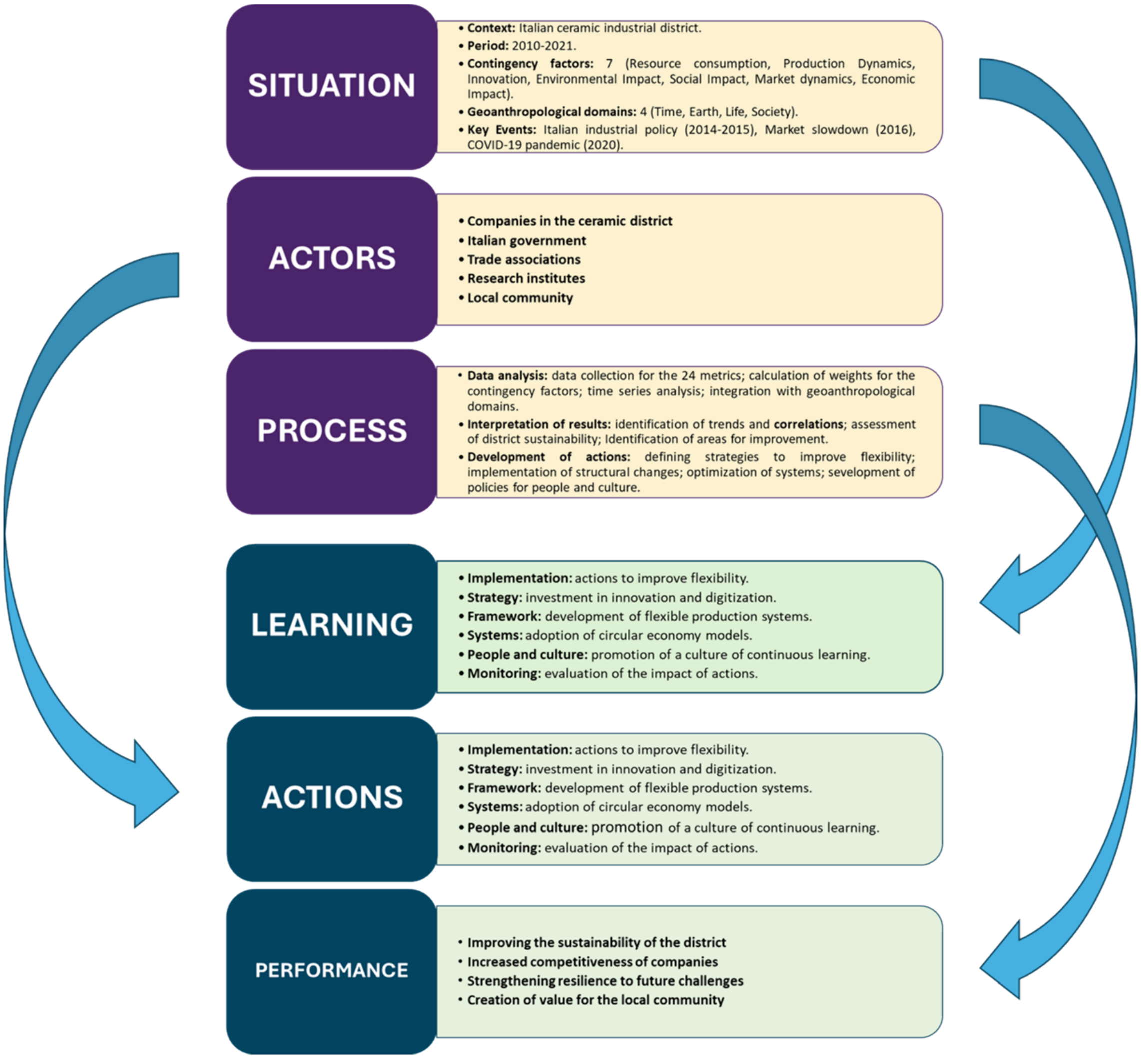


Fig. 9 SAP-LAP framework applied to the case study of the Italian ceramic district

Conclusions

The study of the ceramic district has successfully applied a detailed analysis of seven contingency factors and highlighted their evolution over time. Key historical events, including the Italian government's industrial policy, a market downturn, and the COVID-19 pandemic, significantly influenced these factors. The study contributes by filling the knowledge gap in assessing sustainability performance using a contingency approach.

Theoretical Contributions

The theoretical contributions of this research significantly advance the field of sustainability assessment in industrial districts (IDs). The adoption of a contingent approach, integrated with geoanthropology, provides a holistic view of human–environment interactions in industrial settings, representing a departure from traditional sustainability assessment methods. Geoanthropology enriches the understanding of social, cultural, and economic dynamics within IDs, allowing for a more precise identification of relationships between human actions and long-term environmental and social impacts. Moreover, the integration of Industry 6.0 principles provides an additional perspective on how to improve the sustainability performance of IDs, broadening the vision beyond operational efficiency to include the social, environmental, and economic impacts of industrial activities. The transdisciplinary approach proposed in this study, which incorporates key concepts from different disciplines, provides a solid foundation for the development of strategies and policies aimed at improving the systemic sustainability of IDs in the next Industry 6.0 era. Finally, the adoption of flexible management emerges as a key element in the implementation of such strategies,

Table 2 Framework for navigating Industry 6.0 through the transdisciplinary lens of geoanthropology and systemic sustainability

Geoanthropology's role in industry 6.0	Systemic sustainability's foundations for industry 6.0:
Geoanthropology, which studies the complex interactions between humans and their environment, provides valuable insights for shaping Industry 6.0 in a sustainable and human-centered manner: *Understanding human–environment dynamics* Geoanthropology's expertise in analyzing human–environment interactions can inform the development of sustainable technologies and practices within Industry 6.0 *Addressing global challenges* geoanthropology's holistic perspective can guide Industry 6.0 toward addressing global challenges like climate change, resource scarcity, and social inequality *Promoting cultural sensitivity* geoanthropology's emphasis on cultural diversity can ensure that Industry 6.0 technologies and applications are developed and implemented in a culturally sensitive and inclusive manner	*Systemic sustainability*, which focuses on interconnectedness and long-term thinking, provides a solid foundation for Industry 6.0: *Balancing economic, social, and environmental goals* systemic sustainability's emphasis on balancing economic, social, and environmental considerations aligns with Industry 6.0's potential to address global challenges *Designing for long-term resilience* systemic sustainability's focus on long-term thinking can guide the development of Industry 6.0 technologies that are resilient and adaptable to future changes *Promoting circular economy principles* Systemic sustainability's emphasis on circular economy principles, such as resource efficiency and waste reduction, can inform the design of sustainable manufacturing processes within Industry 6.0
Convergence of geoanthropology and systemic sustainability in Industry 6.0	
The integration of geoanthropology and systemic sustainability provides a powerful framework for shaping **Industry 6.0**:	
Human-centered design geoanthropological insights and systemic sustainability principles can guide the development of human-centered technologies that are not only efficient but also socially and environmentally responsible	
Sustainable innovation the combined expertise of geoanthropology and systemic sustainability can foster sustainable innovation within Industry 6.0, ensuring that technological advancements align with long-term sustainability goals	
Ethical considerations	
Geoanthropology's focus on human values and systemic sustainability's emphasis on ethical principles can ensure that Industry 6.0 technologies are developed and implemented in a responsible and ethical manner	

enabling IDs to adapt quickly and effectively to changing environmental, social, and economic conditions.

In addressing the research questions:

- *RQ1* the research establishes that the contingency approach finds its theoretical grounding in geoanthropology. This integration goes beyond conventional sustainability frameworks and demonstrates the adaptability of the contingency approach to different contexts within IDs.
- *RQ2* the study demonstrates that the contingency approach not only enables but also excels in the design of context-adaptive initiatives within industrial districts. The detailed analysis of seven contingency factors provides a multilevel understanding of the specific challenges and opportunities within the ceramic district. Moreover, the proposed systemic sustainability index, derived from geoanthropological domains, serves as a practical tool to guide the development and implementation of adaptive sustainability initiatives tailored to the unique context of IDSs.
- *RQ3* the transdisciplinary approach proposed in this study incorporates the principles of Industry 5.0, which promote humanity at the core of industrial operations, sustainability as a fundamental element of production, and stakeholder collaboration as a driver of innovation. These principles provide an additional perspective on how to improve the systemic sustainability performance of IDs, shifting the focus beyond operational efficiency to the social, environmental, and economic impacts of industrial activities.
- *RQ4* geoanthropology and systemic sustainability are emerging as key enablers of Industry 6.0, fostering sustainable, symbiotic human–machine interactions. These transdisciplinary approaches drive ethical innovation and resilience, address global challenges, and shape a future of hyper-intelligent human–machine symbiosis in Industry 6.0.

The adoption of a transdisciplinary approach stands out as central to advancing the understanding of systemic sustainability in IDs in the context of Industry 5.0. This approach, embodied in the comprehensive framework shown in Fig. 4, combines essential principles from different disciplines, including systemic sustainability, geoanthropology, and Industry 5.0, highlighting the importance of an integrated view to addressing the complex challenges of IDs. Of particular importance is the integration of geoanthropology into the conceptual framework, which provides a holistic perspective on human–environment interactions in IDs. By providing a sound theoretical and methodological foundation, this approach facilitates a nuanced understanding of the social, cultural, and economic dynamics within IDs, allowing for a more precise delineation of the links between human activities and their lasting environmental and social impacts. As a result, geoanthropology enriches the assessment of systemic sustainability by promoting a deeper understanding of the scope and breadth of human–environment interactions.

For an in-depth exploration of systemic sustainability in industrial districts in the Industry 5.0 era, it is essential to adopt a transdisciplinary approach. This approach, outlined in the proposed framework, combines central concepts from different disciplines, including systemic sustainability, geoanthropology, and Industry 5.0 principles. By emphasizing an integrated perspective, it addresses the multifaceted challenges associated with IDs. At the same time, the infusion of Industry 5.0 principles into the framework enhances understanding and guidance. These principles emphasize the centrality of humanity in industrial operations, the indispensability of sustainability in manufacturing, and the catalytic role of stakeholder collaboration for innovation, broadening the scope beyond operational efficiency to include social, environmental, and economic impacts. This integrated approach comprehensively examines the dynamics that influence the sustainability of IDs and provides a solid foundation for developing strategies to improve systemic sustainability. Moreover, from another perspective, the adoption of organizational flexibility emerges as a key element in the implementation of such strategies. Organizational flexibility enables IDs to adapt quickly and skillfully to changing environmental, social, and economic conditions, facilitating the maintenance of a dynamic balance between stakeholder demands and long-term sustainability goals. Consequently, organizational flexibility aligns well with the proposed conceptual framework and contributes to the optimal and responsible management of IDs in the Industry 5.0 era.

Finally, the emerging setting of Industry 6.0 presents a unique set of challenges and opportunities that require a proactive and transdisciplinary approach. Integrating insights from disciplines such as geoanthropology and systemic sustainability with the principles of Industry 6.0 allows us to develop a more nuanced understanding of the complex dynamics at play. By leveraging Industry 6.0 principles, which emphasize factors such as human–machine symbiosis, hyper-intelligence, and sustainable innovation, we can steer industrial development toward more sustainable and resilient paths. In addition, incorporating geoanthropological perspectives provides valuable insights into the complex interactions between humans and the environment in industrial settings. Understanding these dynamics is critical to designing technologies and practices that not only optimize efficiency but also prioritize environmental protection and social well-being. Similarly, systemic sustainability provides a holistic framework for assessing the long-term impacts and interdependencies of industrial activities, ensuring that development strategies are aligned with broader sustainability goals. By adopting a transdisciplinary approach that synthesizes insights from these diverse fields, we can navigate the complexities of Industry 6.0 with greater foresight and effectiveness. This forward-looking perspective allows us to anticipate emerging challenges such as resource scarcity, climate change, and social inequality while identifying innovative solutions that promote sustainable development. Ultimately, by ensuring that sustainability remains at the forefront of the transition to Industry 6.0, we can build a more resilient and equitable industrial landscape for future generations.

Managerial Implications

The research provides key management insights for the ceramic district and broader industrial contexts. The study highlights the influential role of innovation, digitization, and government policies in shaping production efficiency, market dynamics, economic impacts, and social aspects. By dissecting these drivers, managers gain in-depth insights into the mechanisms of sustainability. Of note is the sector's resilience to challenges due to digitization, internationalization, and significant investment. Managers can use these insights to strengthen their businesses against disruptions and promote a proactive approach to sustainability. The interconnected nature of factors such as innovation and market dynamics requires integrated sustainability strategies. Managers are encouraged to take a holistic view of sustainability, fostering comprehensive and interconnected approaches. The introduction of the systemic sustainability index provides a practical tool for managers. Derived from geoanthropological domains, this index provides a comprehensive metric for measuring overall sustainability. It serves as a valuable compass for decision-making and ongoing strategy evaluation. The geoanthropological model for assessing systemic sustainability in industrial districts recognizes that organizational flexibility is essential to effectively manage the complex interactions among environmental, social, and economic factors that influence the adaptive capacity of firms. As a result, it provides practical insights for managers to promote sustainability through innovation, understand resilience mechanisms, support integrated strategies, and use the systemic sustainability index to make informed decisions.

Limitations and Further Research

While this study provides a comprehensive analysis, it is important to recognize its inherent limitations. The exclusive focus on internal data, valuable for insights into the ceramic district, hinders direct comparisons with other sectors and limits broader applicability and benchmarking.

Future research should investigate the complex interplay between geoanthropology, systemic sustainability, and the emerging Industry 6.0 paradigm. This exploration should consider metrics beyond financial metrics to measure the impact of technology in the innovation domain. Exploring these intersections could provide insights into sustainable practices within the Industry 6.0 framework. Extending the contingency approach to different industrial districts and refining methodologies for better comparability across sectors is critical. Strengthening the theoretical foundations of geoanthropology by integrating it with management theories will enhance its applicability in industrial contexts. In addition, a deeper exploration of systemic sustainability is needed for a holistic understanding. These research directions are essential for refining methodologies and theories, advancing sustainability assessment, and aligning it with the evolving Industry 6.0 landscape. By advancing methodologies and theories, researchers can improve sustainability assessments and guide industries toward greater resilience in the face of technological and environmental change.

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Declarations

Conflict of interest The authors declare no competing interest.

Ethical Approval The authors complied with all ethical norms.

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Key Questions

RQ1. In which specific field of knowledge can the contingency approach for the analysis of the sustainability performance of IDs be embedded?
RQ2. How does the contingency approach to sustainability enable the design of context-adaptive initiatives in IDSs?
RQ3. In the context of Industry 5.0, how can a transdisciplinary approach improve knowledge of the systemic sustainability performance of IDs?
RQ4. How does the emerging paradigm of Industry 6.0 intersect with the principles of a transdisciplinary approach and systemic sustainability?

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CHAPTER II - THERMOECONOMICS AND SYSTEMIC EXERGY MANAGEMENT

This second article develops a core theoretical contribution by establishing a conceptual and methodological bridge between thermoeconomics and management sciences. Historically, corporate performance assessment has emphasized financial metrics, largely neglecting the environmental and resource-efficiency dimensions of organizational operations. This disconnect between economic–financial perspectives and physical-thermodynamic realities has significantly limited our understanding of organizational sustainability.

The article introduces the SYMΞX framework as an innovative paradigm that integrates thermoeconomic principles into the measurement of organizational performance. The study adopts a rigorous theory-building approach, deriving conceptual propositions from an extensive literature review in both thermoeconomics and management, and using them to construct bridges between these domains. These propositions are then synthesized into the SYMΞX theoretical construct through abductive reasoning that seeks the best explanations for the observed phenomena.

The SYMΞX framework focuses on assessing the effectiveness of organizational resource use through exergy-based analysis. The concept of exergy, understood as the maximum useful work that a system in equilibrium with its environment can deliver, provides a more precise and relevant thermodynamic measure than energy for evaluating efficiency in transformation processes. While the First Law of Thermodynamics conserves energy, the Second Law degrades exergy irreversibly in all real processes, making it a superior metric for assessing the physical sustainability of production systems.

This contribution is published in the Global Journal of Flexible Systems Management, an international journal indexed in Scopus and ranked in the first quartile (Q1) in all its categories within Business, Management and Accounting (Business and International Management, Management Information Systems, Strategy and Management, among others). The journal has an SJR indicator of 1.148 and an H-index of 51, reflecting a consolidated trajectory and significant recognition in the field of management and flexible systems. In addition, it is included in the CABS Academic Journal Guide (AJG 2024), in the field of General Management, Ethics, Gender and Social Responsibility, with a rating of 2, further reinforcing its relevance as an outlet for research on management, sustainability, and organizational governance.

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RESEARCH

Thermoeconomics Meets Business Science: Systemic Exergy Management (SYMΞX) as a New Theoretical and Flexible Framework for Sustainability

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Abstract *Historically, corporate assessment of performance has placed a significant emphasis on financial measures, while largely ignoring the broader environmental and resource efficiency implications of organizational operations. This paper introduces a novel framework that integrates thermoeconomic principles into performance measurement. Systemic Exergy Management (SYMΞX) The study employs a theoretical construction approach, deriving conceptual claims from an extensive literature review to bridge the gap between thermoeconomics and existing frameworks. These claims are then synthesized into a novel theoretical construct, designated the SYMΞX framework, through the process of abductive reasoning. This flexible paradigm focuses on measuring the effectiveness of resource consumption in organizations using exergy analysis. Moreover, it enables the development of sustainability performance indicators for assessing impacts on the environment, economy, society, and technology. SYMΞX offers a more comprehensive perspective on organizational performance, accounting not only for financial outcomes but also for resource efficiency and environmental impacts. The study posits that SYMΞX has the potential to advance business science in two main ways: by fostering ethical corporate practices and by enhancing performance measurement. In conclusion, the framework promotes systemic sustainability while offering new avenues for empirical validation and industry-specific applications, thereby ensuring adaptability to evolving business environments.*

Keywords Exergy analysis · Organizational flexibility · Organizational performance measurement · Resource efficiency · Sustainability performance indicators · Systemic exergy management (SYMΞX) · Thermoeconomics

JEL Classification D81 · L61 · L21 · L25 · D24 · Q01

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Introduction

Context and Motivation

The persistently mounting challenges of resource scarcity and climate change necessitate a profound transformation in how companies address sustainability. This transformation must encompass a recognition of the multifaceted and multidimensional nature of sustainability, encompassing environmental, social, economic, and technological dimensions. Despite their utility in understanding market dynamics, conventional economic models are often inadequate for addressing environmental concerns. Such constraints are a consequence of a perspective that prioritizes rapid financial gain, frequently at the expense of long-term environmental degradation (Dey et al., 2020). The prevailing approach to modeling resources such as labor and materials is to treat them as mere economic inputs, with a primary focus on monetary transactions and financial exchanges. This approach fails to consider the physical realities of resource utilization, including the environmental consequences of resource extraction and processing, as well as the depletion of finite natural resources. The discounting strategies employed in traditional models frequently prioritize immediate earnings over long-term consequences. Such an approach may result in unsustainable behaviors that prioritize immediate financial gain over the long-term environmental impact (Brozovic, 2020). The prevailing practices and standards in the field of sustainability are unable to effectively reflect the evolving nature of sustainability challenges. By failing to account for the evolving nature of environmental challenges and resource limitations, these practices offer a static representation of an environmental baseline that companies are expected to adhere to (Lakner et al., 2024). Conventional models hardly give the environment's ecological carrying capacity any thought. This can cause companies to surpass the capacity of ecosystems to absorb pollutants and trash, therefore degrading the surroundings (Deng et al., 2024). These restrictions highlight the necessity for the development of a novel economic paradigm that incorporates environmental concerns into the decision-making processes of corporations. This is where thermoeconomics, a field that integrates economic principles with the laws of thermodynamics, presents a promising avenue for resolution. The field of thermoeconomics provides a framework that recognizes the physical limits that control resource consumption and environmental impact. This framework combines the ideas of economics with the laws of thermodynamics (Jamil et al., 2020).

Exergy, a measure of the useful energy available in a system, is a fundamental concept in thermoeconomics (Querol et al., 2013). In contrast to traditional forms of energy, which are susceptible to loss or degradation, exergy retains its inherent value unless there is a transfer of mass or heat. This highlights the significance of energy conservation and waste reduction in economic systems. By underscoring the interconnection between human conduct and the natural environment, thermoeconomics challenges the conventional economic perspective that prioritizes the human element (Tallgauer & Schank, 2024). It recognizes that the availability of natural resources and the capacity of the environment to manage waste impose constraints on economic activity. The integration of physics and ecological concepts in thermoeconomics provides a more comprehensive outlook on the sustainability of economic systems (Arslan & Yilmaz, 2024). This paper proposes a new theoretical framework for systemic sustainability, the exergy-based management model, which integrates thermoeconomics with business science. This novel approach not only underscores the significance of exergy preservation in economic operations but also underscores the necessity for organizational flexibility (Dimple & Tripathi, 2024; Rumman & Alqudah, 2024; Singh et al., 2021a, b). In the context of this theoretical contribution, organizational flexibility is a crucial factor in enabling dynamic adaptation to changing economic conditions, thereby ensuring sustainable and resilient management in the long term (Pandey et al., 2024).

This paper introduces the Systemic Exergy Management (SYMΞX) framework, a novel theoretical model that fuses thermoeconomic principles with business science to create a holistic sustainability assessment tool. In contrast to existing models, SYMΞX is distinctive in its integration of exergy analysis with corporate performance evaluation, thereby enabling organizations to assess financial outcomes and resource efficiency concurrently. This novel approach addresses deficiencies in the existing literature by demonstrating the potential of thermodynamic principles as a means of enhancing corporate performance metrics, thereby facilitating the development of sustainable business practices that are firmly grounded in systemic efficiency (Tsatsaronis, 2011). Similarly, Gong et al. (2018) emphasize the necessity for dynamic sustainability performance frameworks based on real-time data, which can enhance decision-making processes pertaining to environmental, social, and governance (ESG) initiatives. Moreover, for readers less familiar with thermoeconomics, it is essential to provide clarification regarding the key terms utilized throughout this manuscript. The term "exergy" is used to quantify the potential for useful work within an energy flow, whereas "entropy" is employed to indicate the extent of disorder in a system. This represents the energy losses that are unavailable for productive work. The SYMΞX framework is founded upon thermodynamic principles, which enable it to assess resource efficiency and sustainability.

Research Design

This study adopts a theoretical building approach that uses abductive inference to integrate concepts from thermodynamics and management science (Rivard, 2021). This method entails the construction of a novel theoretical framework through the integration of concepts and principles drawn from disparate disciplinary domains. In this instance, the integration of thermodynamics, which examines the transformation of heat, and management science, which concerns the organization and control of activities, resulted in the development of a novel conceptual framework. This framework was utilized to investigate the potential applications of thermoeconomics in the domain of business performance measurement (Vila-Henninger et al., 2022).

The initial phase of the study entailed a comprehensive examination of pertinent scholarly literature. A variety of scholarly books and papers from disparate fields, including economics, sustainability studies, management science, and thermodynamics, were subjected to examination. The principal objectives of this research were to identify the fundamental concepts and theories pertaining to thermoeconomics, sustainability reporting, and corporate performance assessment. This review formed the basis for the development of several conceptual propositions (Lager & Simms, 2023). The objective of these propositions was to establish a link between the potential contributions of thermoeconomics to the field of sustainability management and the performance assessment frameworks currently in use. Subsequently, an abductive reasoning process was employed, following the completion of the literature review. Abductive inference is an iterative process that involves moving between empirical observations and theoretical explanations in order to refine and construct new theoretical frameworks (Shepherd & Suddaby, 2016). The study integrated the developed conceptual propositions through this process, resulting in a novel theoretical abstraction. This abstraction serves as a framework for incorporating thermoeconomics principles into corporate performance measurement.

Structure of the Work

The following is a description of the organization of the article. In order to establish the fundamental principles of business science and thermoeconomics, the section entitled "Research Design" presents a comprehensive review and analysis of the essential literature in the field. The theoretical building process and research analytical tools are elucidated in Section "Theoretical Background." The Systemic Exergy Management (SYMΞX) framework is elucidated in Section "Systemic Exergy Management (SYMΞX)," wherein its fundamental tenets and practical applications are also expounded. The impact of SYMΞX on management theories is investigated in the "Contribution to the Development of Management Theories" section, with a particular emphasis on its capacity to be integrated seamlessly with existing paradigms and its suitability for bridging model gaps. In the section entitled "Enhancing Organizational Flexibility Through SYMΞX," real-world examples are provided to illustrate the way the novel framework is applied to a variety of business tasks. The primary findings are summarized in the "Conclusion" section, accompanied by a discussion of potential policy recommendations.

Theoretical Background

In the contemporary historical period, when the impact of human activity on the planet is more evident than ever, it is imperative to adopt a comprehensive approach to sustainability (Peng et al., 2021). The classic three pillars of sustainability (economy, environment and society) have long provided a framework for understanding and addressing the challenges of sustainable development (Srivastava et al., 2022) including through the sustainable development goals (SDGs) (Colasante et al., 2024). However, the accelerated evolution of global systems has rendered the conventional approach to analysis inadequate. A more integrated perspective that transcends traditional boundaries is necessary to comprehend the rapidly changing complexity of these systems. This necessitates a shift in focus from proximate economic advantages to a more comprehensive examination of the long-term consequences of organizational and individual actions on the natural environment and social systems (Piccarozzi et al., 2022). The application of innovative approaches to sustainability knowledge, such as thermoeconomics, can facilitate a comprehensive assessment of the sustainability of processes and systems. This approach ensures that the ability of future generations to meet their needs is not compromised (Ahmad et al., 2023). Thermoeconomics, which combines the principles of thermodynamics with economic theory, offers a unique perspective on sustainability (Valentinov, 2021). The application of thermoeconomics enables the accurate assessment of the true costs associated with economic activities. This is achieved by the quantification of energy flows and the identification of exergy losses. In contrast to conventional economic analysis, which frequently concentrates exclusively on financial costs, thermoeconomics takes into account environmental, social, and resource depletion expenses. For example, consider an industrial process that generates high levels of air pollution and public health impacts (Wang et al., 2022) but also on buildings (Ruffolo et al., 2023); thermoeconomics can reveal the significant energy costs associated with this pollution and its social impacts, providing a more accurate assessment of the total cost of production (Fu & Su, 2021). The integration of complex systems thinking into sustainability studies is a crucial endeavor, as it enables the observation of the interconnectivity of all elements within a system and the comprehension of how alterations in one component can precipitate ripple effects across the entire system (West et al., 2020). This perspective is essential for the development of strategies that are not only effective in the short term but also sustainable in the long term.

The Contribution of Thermoeconomics to Management Studies

The field of thermoeconomics has the potential to make a substantial impact on the field of management science. By providing a framework for integrating economic analysis with the fundamental principles of thermodynamics, particularly the concept of exergy, thermoeconomics offers a unique opportunity to advance our understanding of complex systems. A fundamental concept in thermodynamics, exergy is defined as the maximum useful work that can be extracted from a system in each state, with the environment serving as a reference point. It represents the potential for a system to perform work while maintaining equilibrium with its surrounding environment. In essence, exergy is a measure of the quality of energy, distinguishing between high-quality energy, which can be readily converted into useful work, and low-quality energy, which is difficult to utilize effectively (Catrini, Cipollina, et al., 2018). This integration facilitates a more comprehensive understanding of the efficiency and sustainability of production and consumption processes. In the field of management science, thermoeconomics can be employed to optimize the design and operation of energy systems, improve resource allocation, and enhance environmental performance (Liu & Shen, 2022) and increased flexibility for businesses (Litvinova et al., 2023). In the contemporary business environment, characterized by rapid change and uncertainty, flexibility is a crucial attribute for organizations to possess. The ability to adapt to shifts in resource availability, energy costs, and environmental regulations is imperative for businesses to survive and thrive (Yuan & Zhang, 2020). For instance, thermoeconomic analysis can assist in the identification of the most efficient methodologies for the utilization of energy and materials in production processes, which may result in cost savings and a reduction in environmental impact (D'Adamo et al., 2023). It can also provide insights into the true economic value of goods and services, considering the energy and material inputs required for their production (Casisi et al., 2023). In addition, thermoeconomics can contribute to the development of sustainable business models (Barletta et al., 2024) that consider the long-term availability of resources and the environmental consequences of business activities (Ja'fari et al., 2023). By assessing the energy consumption of different processes, managers can make more informed decisions that are in line with sustainability goals (Karthikeyan & Praveen Kumar, 2023). The theoretical relationship between thermoeconomics and management can be summarized in the following key points:

- **Efficiency and Exergy:** The concept of exergy, which represents the maximum useful energy that can be extracted from a system for performing valuable tasks, is a central tenet of thermoeconomics. This concept is closely aligned with the principles of efficiency in management, which seek to maximize output while minimizing input resources. By identifying and reducing exergy losses, managers can optimize resource utilization and enhance overall system efficiency (Ekrataleshian et al., 2021).
- **Cost Allocation and Exergoeconomic Analysis:** It is a specialized field that integrates the principles of thermodynamics and economics to optimize energy systems. The assignment of monetary value to exergy allows for a more precise allocation of costs to the various components and processes involved. This approach designated "exergoeconomic analysis," fosters transparency in pricing and facilitates informed decision-making. Consequently, it has become an indispensable instrument for engineers and economists striving to enhance the efficiency and sustainability of energy systems (Aghbashlo & Rosen, 2018).
- **Sustainability and Exergy:** The principles of thermoeconomics are aligned with those of environmental stewardship and long-term economic viability, as they promote the sustainable utilization of energy and resources. By optimizing exergy utilization, managers can reduce waste and conserve valuable resources, thereby contributing to the development of a more sustainable business model**.** (Erzen et al., 2021).
- **Process Optimization and Thermoeconomic Indicators:** The application of thermoeconomic analysis provides a means of identifying and quantifying inefficiencies inherent to industrial processes. By analyzing exergy destruction and losses, managers can identify areas for improvement and optimize process designs, which ultimately leads to reduced costs and increased productivity (Cao et al., 2022).
- **Resource Management and Exergoeconomic Benchmarks:** The application of thermoeconomic benchmarking enables managerial personnel to undertake comparative analyses of the efficiency of disparate processes or systems, thereby furnishing a foundation for the formulation of improvement initiatives. By establishing exergoeconomic benchmarks, organizations can monitor their progress toward optimized resource utilization and cost-effectiveness (Ogorure et al., 2024).

A schematic representation of the concepts is presented in Table 1, which emphasizes the interrelationship between exergy (a measure of the maximum useful work that can be

Table 1 Relationships between key concepts in thermoeconomics and management science

Key concepts	Thermoeconomics	Management
Exergy	Maximum useful work that can be extracted from a system	Efficiency in resource utilization
Entropy	Measure of disorder or unavailable energy	Inefficiency in resource utilization
Economic efficiency	Ratio of output to input in terms of resources	Ability to achieve organizational goals with minimum resource expenditure

extracted from a system), entropy (a measure of disorder or randomness), and economic efficiency. This framework establishes links between key management areas, including resource allocation (the process of allocating resources to specific activities), sustainability (meeting the needs of the present without compromising the ability of future generations to meet their own needs), resilience (the ability to recover from perturbations), decision making (the process of selecting the best course of action) and innovation (the introduction of new ideas, products or services).

A review of the key concepts presented in the table reveals that exergy represents the maximum useful work that can be extracted from a system in thermoeconomics. Consequently, it gauges the quality or accessibility of energy, considering both the energy density and the capacity to perform work. In the context of management, energy can be considered analogous to the efficiency of resource utilization, emphasizing the extent to which resources are transformed into valuable outputs. Entropy serves to quantify the degree of disorder or randomness intrinsic to a given system. It thereby indicates the extent of energy that is unavailable for useful work due to the inherent irreversibility and losses inherent to such processes. In the field of management science, it signifies the inefficiency of resources, which ultimately results in waste and a decline in economic efficiency. In the context of management, economic efficiency is defined as the ratio of output to input concerning resources such as energy, materials, or labor. It reflects the effectiveness with which resources are utilized in order to achieve organizational flexibility. The field of thermoeconomics is concerned with aligning economic efficiency with the minimization of exergy degradation and entropy production.

Table 2 applies thermodynamic principles (Ağbulut, 2022) to management, advocating a cross-disciplinary approach to energy exchange. It correlates the fundamental tenets of thermodynamics with a range of managerial, social, technological, and physical interpretations. This comprehensive framework permits the examination of energy efficiency and resource utilization across a range of scenarios. A comprehensive approach is thereby attained, whereby thermodynamic principles are translated into practical strategies for the management of resources, technological innovation, and societal accountability. As illustrated in Table 2, a comprehensive and detailed multidimensional description of the principles of thermodynamics is provided below.

Principle 0 (Zeroth Law)

- **Physical Interpretation:** The zeroth law of thermodynamics establishes that if two systems are each in thermal equilibrium with a third system, they are also in equilibrium with each other (Honig, 2014).
- **Managerial Interpretation:** Organizations should aim to balance their exergy levels to direct valuable resources toward the most efficient processes, aligning with energy efficiency principles (Naletov et al., 2020).
- **Social Interpretation:** Societies must pursue equitable conditions, ensuring resource access for all individuals, reflecting fairness and justice in resource distribution (Ali & Kamraju, 2023).
- **Technological Interpretation:** Prioritization of technologies that optimize energy extraction and minimize entropy is essential, resonating with resource optimization goals (Williams, 2024).

Principle 1 (First Law)

- **Physical Interpretation:** The first law of thermodynamics asserts the constancy of total energy in an isolated system over time (Aghion & Green, 2023).
- **Managerial Interpretation:** Organizations should engage in resource conservation and exergy efficiency, ensuring sustainable operations without resource wastage (Dehghani & Yoo, 2020).
- **Social Interpretation:** Societies must embrace environmental stewardship, conserving resources for future generations and minimizing ecological impact (Hassan et al., 2021).
- **Technological Interpretation:** The adoption of technologies that enhance energy efficiency and reduce waste is crucial, reflecting the principles of sustainable technology development (Zevenhoven, 2021).

Table 2 Managerial interpretation of thermodynamic principles

Thermodynamic principle	Key concept	Managerial interpretation	Social interpretation	Technological interpretation	Physical interpretation
Principle 0 (Zeroth Law)	Equivalence of Exergy	Equalize exergy levels	Promote equity and fairness	Utilize efficient technologies	Energy equivalence
Principle 1 (First Law)	Exergy Conservation	Conserve resources	Embrace sustainability practices	Optimize resource allocation	Energy conservation
Principle 2 (Second Law)	Exergy Degradation	Minimize waste	Reduce negative externalities	Develop innovative processes	Entropy increase
Principle 3 (Third Law)	Asymptotic Approach to Entropy	Optimize resource utilization across all conditions	Promote continuous improvement	Adopt adaptive technologies	Entropy maximum at absolute zero

Principle 2 (Second Law)

- **Physical Interpretation:** The second law of thermodynamics dictates that the entropy of an isolated system will invariably increase over time (Neri, 2020).
- **Managerial Interpretation:** Organizations are encouraged to pinpoint and rectify inefficiencies, aiming to reduce exergy degradation and bolster long-term sustainability, in accordance with continuous improvement principles (Fleck, 2023).
- **Social Interpretation:** Societal efforts should focus on curtailing negative externalities like pollution and resource overuse, reflecting a commitment to environmental responsibility (Westbroek et al., 2020).
- **Technological Interpretation:** The development and implementation of innovative processes and technologies that curtail entropy and waste align with waste reduction objectives (Prajapati et al., 2024).

Principle 3 (Third Law)

- **Physical Interpretation:** The third law of thermodynamics states that the entropy of a system approaches a maximum value as the temperature approaches absolute zero (Buffoni et al., 2022).
- **Managerial Interpretation:** Organizations should strive for exergy efficiency across the entire range of operating conditions, maximizing resource utilization and minimizing waste generation. This aligns with the concept of wide-range optimization, which emphasizes the need to consider resource efficiency at all stages of the production process (Mimkes, 2017).
- **Social Interpretation:** Societies should strive for continuous improvement in social welfare and equity across all demographics and socioeconomic groups. This aligns with the concept of inclusive development, which focuses on ensuring that the benefits of progress are shared equitably (Tsekov, 2023).
- **Technological Interpretation:** Technologies that are adaptable to various operating conditions and can function efficiently over a wide range of temperatures should be prioritized. This aligns with the concept of universal applicability, which emphasizes the need for technologies that can be used in diverse settings and under varying conditions (X. Chen et al., 2024).

Figure 1 presents a conceptual diagram that elucidates the interrelationships between pivotal concepts in thermoeconomics and management. The diagram's core concepts are exergy, entropy, and economic efficiency, which are represented as interconnected nodes. Exergy represents the maximum useful work that can be extracted from a system, while entropy measures the degree of disorder or unavailable energy. Economic efficiency is defined as the ratio of output to input in terms of resources. The arrows indicate the dynamic interactions between these concepts, thereby demonstrating how thermoeconomics integrates with management principles to optimize resource use, minimize waste, and improve overall system efficiency.

Theory of Thermoeconomic Management

The concept of thermoeconomics represents a novel approach that integrates thermodynamic principles with financial considerations, offering a novel system for coordinating business activities toward feasible development (Cardullo & Liu, 2017). By establishing a connection between the physical and financial realms, this unconventional approach aims to optimize financial flows with a focus on asset productivity and natural preservation. The fundamental concept of thermoeconomics is energy, which

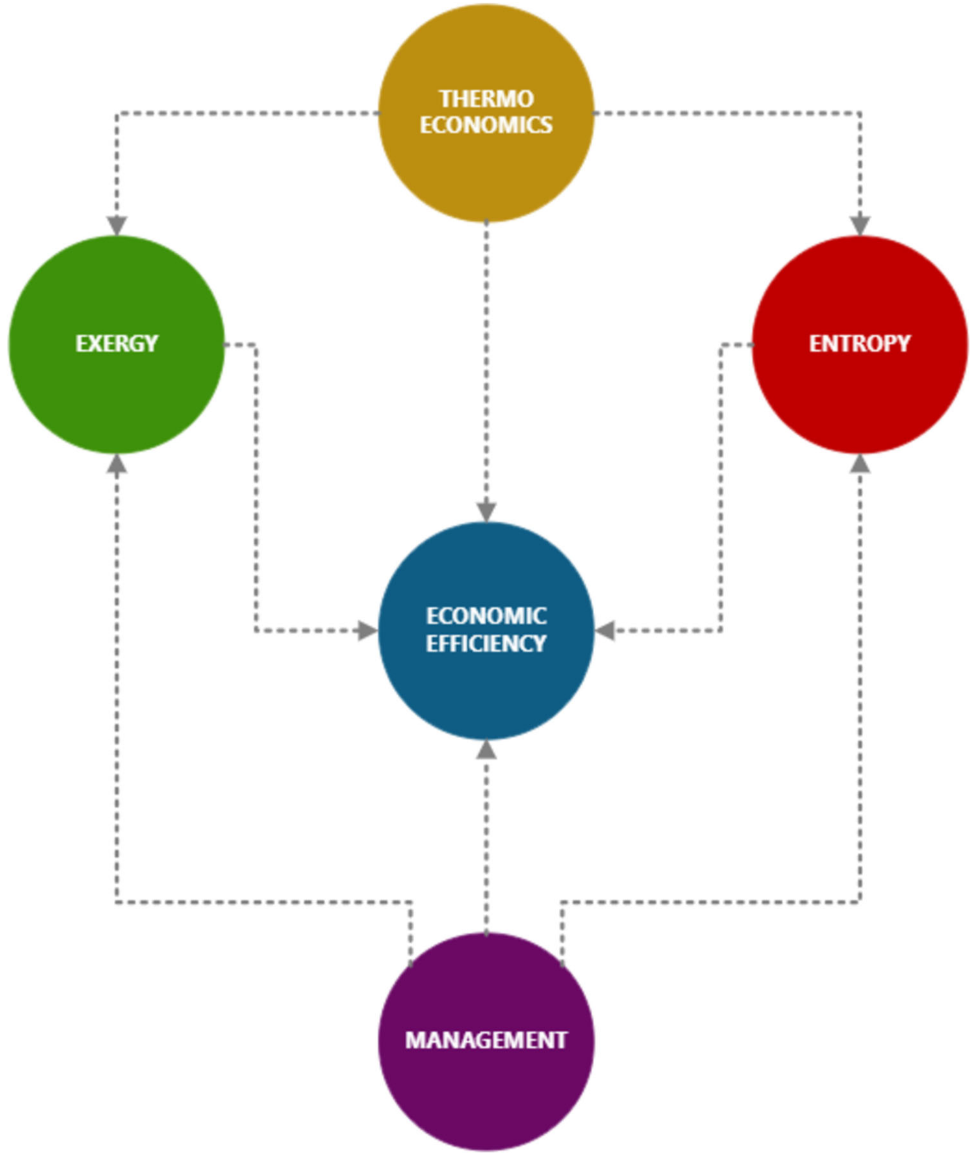

Fig. 1 Conceptual diagram of Thermoeconomics and Management

can be defined as a thermodynamic quantity representing the potential work that can be extracted from a system. While energy is subject to variation, exergy remains constant in the absence of net mass or heat exchange (Ghaebi et al., 2011). This underscores the critical necessity to curtail energy wastage and conserve energy in business operations. Consequently, thermoeconomics utilizes energy flow analysis to identify inefficient processes and potential avenues for asset preservation (Mahmoudan et al., 2021).

The comprehensive approach adopted by thermoeconomics enables the integration of ecological concepts with the fundamental laws of physics. This perspective asserts that economic activity is inherently constrained by the availability of natural resources (Frangopoulos & Dimopoulos, 2024). Furthermore, thermoeconomics offers a more comprehensive grasp of the complex interconnections between the environmental, social, technological, and economic dimensions of sustainability. It acknowledges the interdependence between human activity and the natural world, challenging the anthropocentric perspective that has traditionally informed economic theory (Sciubba, 2019). It is possible to evaluate the sustainability of economic systems using novel analytical approaches that thermoeconomics may offer. This novel method has the potential to provide decision-makers with new tools for redefining policies that enhance organizational efficiency, reduce environmental effects, and support long-term sustainability. This is achieved by measuring energy flows and accounting for ecological limits (Simpson & Edwards, 2011).

Proposition 1 (P1): *Thermoeconomics, a convergence of thermodynamics and economics, offers a holistic approach to sustainable development that optimizes resource use and minimizes environmental impact.*

The field of thermoeconomics extends beyond the conventional boundaries of economic study. The fundamental ideas of thermoeconomics can be applied at various economic levels, including the mesoeconomic (industry) and microeconomic (business) levels, despite its initial development at the macroeconomic level (Chamchine et al., 2006). It is conceivable that thermoeconomics may prove to be an efficacious instrument at the meso-economic level, capable of influencing the entirety of a company toward the adoption of sustainable practices. Those in positions of authority within the industry, in conjunction with policy officials, are able to identify sectors where there is a notable decline in energy efficiency by undertaking an examination of the energy flows within specific industries (Dincer, 2002). The data presented herein can facilitate the implementation of targeted initiatives, including the promotion of energy-efficient technology and the facilitation of industrial collaboration aimed at the development of optimal resource utilization procedures (Rosa & Beloborodko, 2015). From an industrial perspective, this strategy has the potential to markedly diminish overall energy utilization and environmental impact. Similarly, thermoeconomics enables businesses to make data-driven decisions that improve their sustainability on a microlevel. The application of exergetic analysis enables businesses to identify inefficiencies in their manufacturing processes. Such an approach can identify potential avenues for enhancement, including the selection of raw materials with a higher embodied energy (thereby necessitating less processing) or the optimization of heating or cooling systems (Caglayan & Caliskan, 2022). By reducing energy degradation in their operations, businesses may achieve significant cost savings and environmental benefits. It is possible to achieve a more feasible item life cycle if the organization adopts the use of lighter, more energy-intensive materials that utilize less energy during the manufacturing process. The thermoeconomics may facilitate a cascading impact of beneficial financial and natural outcomes by comprehending and optimizing the flow of assets and energies at each level, from small businesses to entire divisions. This multi-level approach guarantees that asset effectiveness and natural obligation become an integral component of all financial operations, thereby providing a comprehensive framework for achieving economic advancement (Calise et al., 2006).

Proposition 2 (P2): *By integrating the laws of physics with economic principles, thermoeconomics can understand and optimize the flow of resources and energy and help guide decision-making toward more sustainable outcomes.*

A novel approach to product creation and marketing strategies is given by thermoeconomics (Cabello, 2022). Designers can constrain energy degradation and entropy ordering in their products, minimizing their impact on the environment and optimizing resource utilization (Abadías Llamas et al., 2020). This is frequently achieved by examining the thermodynamic aspects of materials and energy flows. Furthermore, thermoeconomic analysis can facilitate the selection and development of materials and production methods that minimize energy consumption and environmental impact, ultimately resulting in the creation of more environmentally conscious products (Wu et al., 2021). Furthermore, thermoeconomics can inform marketing plans by emphasizing a product's efficiency and sustainability. The application of thermal economic concepts allows companies to demonstrate the environmental benefits of their products, including reduced energy consumption, more efficient use of resources, and the minimization of waste (Rosa & Beloborodko, 2015). It is possible for businesses to gain a competitive advantage by targeting consumers who are environmentally concerned with marketing messages that are aligned with sustainability ideals. Moreover, thermoeconomics facilitates the traceability and transparency of supply chains, which enables businesses to effectively communicate the product's sustainable credentials (Catrini et al., 2018a, 2018b).

Proposition 3 (P3): *Thermoeconomics innovates product design, manufacturing, and supply chain management to promote resource efficiency, sustainability, and consumer engagement.*

Financial measures such as revenues, profit margins, and return on investment have historically been employed to evaluate the performance of business entities (Tasáryová et al., 2021). Notwithstanding, these indicators are inadequate for encompassing the full spectrum of organizational benefits, particularly with respect to resource efficiency, social responsibility, and environmental sustainability (Imeni & Edalatpanah, 2023). The application of thermoeconomics facilitates a comprehensive understanding of organizational performance by integrating thermodynamic principles into performance measurement systems, thereby addressing this constraint (Li, 2016). Exergy-based accounting represents a novel statistical approach that can be integrated into thermoeconomics. It assesses the efficiency with which resources are utilized within a company, evaluating both the effectiveness of resources and their impact on the environment, in addition to the financial value generated by organizational operations (Rocco et al., 2014). The integration of exergetic analysis into performance evaluation allows businesses to identify inefficiencies in the usage of resources and develop sustainable performance (Haydargil & Abuşoğlu, 2018).

Proposition 4 (P4): *Thermoeconomics promises to transform business management by introducing metrics that capture economic, environmental, and resource efficiency, incentivize sustainability, and improve organizational performance.*

Using propositional logic (Steen & Fuenmayor, 2024), the following theoretical statement can be made based on the previous propositions:

$$T1\,(Overall\,Theory\,1)\ = P1 \wedge P2\ \rightarrow\ (P3 \wedge P4)$$

where:

1. **T1 (Overall Theory 1):** represents the overall theory we are building.
2. **P1 ∧ P2:** This conjunction underlies this part of the theory. It states that thermoeconomics (P1) offers a holistic approach to sustainability (P1) by integrating thermodynamics (understanding resource flows) with economics (decision-making) (P2). This combined approach allows for optimizing resource use and minimizing environmental impact (P1).
3. **P3 ∧ P4:** This conjunction represents the potential outcomes of applying thermoeconomics in business management. It suggests that thermoeconomics can lead to:
   - **P3:** Innovation in product design, manufacturing, and supply chain management, fostering resource efficiency, sustainability, and consumer engagement. By understanding resource flows and their environmental impact, thermoeconomics guides development toward sustainable practices and engages consumers who value sustainability.
   - **P4:** Transformation of business management by introducing metrics that capture not only economic performance but also environmental and resource efficiency. These metrics incentivize sustainability within the organization and contribute to improved overall performance.

In light of these considerations, T1 underscores the pivotal role of a holistic approach (P1) and an understanding of resource flow (P2) in achieving both innovation in sustainability practices (P3) and a transformation of business management (P4).

Thermoeconomic Management Across Dimensions

As we navigate the intricate terrain of contemporary management, it is evident that conventional strategies for maximizing profit within market limitations are no longer adequate. The urgent issues of environmental degradation and resource depletion demand a fundamental transformation of economic paradigms (Spash, 2020). The concept of exergy, a pivotal yet frequently overlooked aspect of energy, serves as the foundation for this transformation. The objective of traditional management has consistently been the maximization of efficiency, or the achievement of greater results with the same or fewer resources (Martínez-Alonso et al., 2020). But this approach often ignores the highly valuable component of energy available for work: exergy (Grainger & Smith, 2021). This oversight has significant implications for the field of thermodynamics, as any transformation process will eventually result in a decrease in exergy. This phenomenon signifies the loss and waste of valuable work potential in the form of heat (Ustaoglu et al., 2022). The importance of understanding and addressing exergy losses in organizational processes is underscored by this omission. By implementing this approach, we can reduce our environmental impact and optimize resource utilization. By prioritizing sustainability and conscientious resource management, it is possible to develop a management style that is more effective, efficient, and environmentally friendly, with a positive impact on both the environment and the business. This shift in perspective can be achieved by adopting the concept of exergy as a foundational principle (He et al., 2020). It is of the utmost importance to recognize that exergy serves as a powerful operational instrument, capable of addressing real-world issues both in theory and practice. By adopting a more holistic perspective, we can ensure that future generations enjoy a more sustainable future.

Proposition 5 (P5): *Traditional profit-maximizing approaches to management are inadequate in the face of resource depletion and environmental concerns. Embracing exergy can optimize resource use and minimize environmental impact, promoting sustainability and responsible resource management.*

The concept of exergy represents a fundamental tenet in thermoeconomics, offering a means to ascertain the intrinsic value of our energy resources. Exergy represents the measure of the usable work potential inherent within an energy flow, as opposed to energy, which is inherently diminished with each change (Rúa Orozco et al., 2024). The concept is significant in that it illustrates the true value of a resource when it is utilized for the achievement of meaningful objectives. For businesses seeking to be responsible custodians of their resources, reducing energy consumption represents a significant challenge (Bernat et al., 2022). The conventional approach to enhancing efficiency typically concentrates on curbing energy usage. However, in the context of today's constrained resource scenario, this strategy is inadequate (Wohlfarth et al., 2020). By employing energy analysis, organizations can identify areas where critical resources are being expended ineffectively or in a wasteful manner. This analytical approach offers valuable insight into the utilization of resources within a given system (James et al., 2020). The implementation of exergy analysis enables organizations to optimize the utilization of their resources, reduce waste, and extend the lifespan of essential resources (Nikam et al., 2021). By reducing energy losses across their operations, this strategy also assists businesses in mitigating their environmental impact (G. Singh et al., 2021a, 2021b). Energy loss is a pervasive phenomenon that occurs at each stage of the production process, frequently resulting in the generation of waste heat and the depletion of resources (Gupta et al., 2022). By identifying instances of resource misuse or waste, exergy analysis enables companies to achieve financial savings and optimize resource utilization, thereby gaining a competitive advantage in their market (Naderi et al., 2021). For companies striving to optimize their resource utilization, mitigate their environmental impact, and maintain competitiveness in a context of constrained resources, it serves as a highly effective instrument (Brändström & Eriksson, 2022).

Proposition 6 (P6): *Exergy, a pivotal concept in thermoeconomics, uncovers energy resource value. Addressing exergy loss boosts resource efficiency, cuts waste, and lowers environmental impact, enhancing organizational flexibility and business competitiveness.*

The implementation of an innovative management strategy founded upon thermoeconomic principles is imperative for the effective resolution of these issues. It is imperative that this strategy transcends the conventional approaches to sustainability that have been employed thus far and concentrates on maximizing resource efficiency throughout the entire value chain (Fernandes et al., 2020). This strategy should transform organizational procedures and decision-making, guided by the idea of exergy (Fernandes et al., 2020). A set of fundamental concepts that facilitate our understanding of energy and its role in optimizing resources form the basis of thermoeconomics. The principle of exergy equivalence serves to illustrate that the total exergy within a closed system remains constant (Romero & Linares, 2014). This suggests that, while energy cannot be generated or destroyed, it can undergo a transformation in form. For businesses seeking to monitor energy flows throughout their operations and allocate resources in an optimal manner, this principle is of paramount importance. The second principle, exergy conservation, emphasizes the minimization of exergy degradation. It is inevitable that a certain amount of energy will be converted into useless heat during a process. The objective of thermoeconomics is to reduce this energy loss by streamlining procedures and advancing technology (Chen et al., 2024). It is possible for organizations to reduce waste and make optimal use of their valuable resources by following this approach. The third principle, the Asymptotic Approach to Entropy, acknowledges that all systems ultimately reach a maximum entropy state from which no further usable work can be derived. In order to reduce energy deterioration and reach a condition closer to optimal utilization, thermoeconomics, on the other hand, promotes a never-ending quest of improvement, pushing firms to aim for constant innovation and process optimization (Dobija & Renkas, 2021). In conclusion, the concept of systemic sustainability underscores the necessity for a comprehensive approach to sustainability that integrates the technological, social, economic, and natural aspects of sustainability (Khlif et al., 2022). It is possible for organizations to make decisions that are beneficial to society, the environment, and their financial line of business when they take these dimensions of energy flows into account. This strategy recognizes that sustainability necessitates the attainment of a delicate equilibrium between these competing objectives, encompassing both environmental conservation and economic growth (Gabbi et al., 2021).

Proposition 7 (P7): *The total exergy within a system remains constant, and exergy can be transformed but not created or destroyed, guiding organizations to optimize resource allocation and minimize waste.*

Proposition 8 (P8): *Continuous innovation and process optimization are necessary to minimize exergy degradation and achieve a state closer to perfect utilization.*

Proposition 9 (P9): Minimizing exergy degradation is crucial for maximizing resource utilization and achieving systemic sustainability, balancing environmental, social, technological and economic interests.

In light of the aforementioned analysis, it can be posited that thermoeconomic management (TM) represents a strategy (Kopnina, 2017) that seeks to integrate the fundamental principles of thermodynamics (Varbanov et al., 2020) into the very core of business operations (Nadi & Górnicki, 2022). This integration is undertaken with the objective of effecting a transformation in our conceptualization of sustainability (Abeysekera, 2022). This innovative method provides a comprehensive framework for maximizing resource use and reducing environmental impact in all aspects of a business. Adoption of the thermoeconomic approach allows businesses to optimize resource utilization, modify operational procedures, and reduce their ecological impact in a substantial and quantifiable manner (Jiménez & Baena, 2024). It can be argued that thermoeconomic management (TM) represents an effective technique for maximizing energy efficiency and reducing waste in the physical realm (thermophysics) (Clairand et al., 2020). TM identifies areas of inefficiency and directs interventions to enhance energy efficiency and mitigate energy losses by examining energy flows within organizational activities. By determining the exergy content of resources and directing activities to maximize their use while minimizing their depletion, TEM also increases resource efficiency (Llamas et al., 2024). T This entails the implementation of tactics such as material recycling, reuse, and waste-to-resource conversion, which utilize the energy content of waste streams to extract additional value. By employing exergy analysis, TM facilitates decision-making processes within the management dimension (thermobusiness) by providing managers with insight into the exergetic performance of various solutions, thereby enabling well-informed choices that prioritize waste minimization and resource efficiency (Selicati & Cardinale, 2021). Moreover, the integration of energy considerations into organizational planning facilitates the development of sustainable business models and strategies for businesses. This allows them to align their operations with the values of environmental stewardship and resource conservation. Within the social dimension (thermosocial), TM fosters an organizational culture of resource conservation and environmental responsibility, thereby promoting employee well-being and engagement in sustainability projects (Arias et al., 2023). TM facilitates the integration of broader social concerns into the decision-making processes of stakeholders by enhancing their awareness of the social implications of business actions and products (Cano-Londoño et al., 2022). In addition, TM guides the implementation of energy-efficient technologies and processes within the thermo-technological domain. This is achieved by evaluating their exergetic performance and identifying areas for improvement (Silva et al., 2020).

Proposition 10 (P10): *Thermoeconomic management optimizes energy use and minimizes waste by analyzing exergy flows, guiding interventions for improved efficiency and resource utilization.*

Proposition 11 (P11): *Thermoeconomic management informs decision-making through exergy analysis, enabling resource-efficient and waste-minimizing choices, fostering sustainable business models.*

Proposition 12 (P12): *Thermoeconomic management promotes employee engagement in sustainability by fostering resource conservation and awareness of social impacts.*

Proposition 13 (P13): *Thermoeconomic management guides adoption of energy-efficient technologies, development of waste-to-resource solutions, and integration of renewable energy sources.*

Based on the previous proposition, the following theoretical statement can be made:

$$T2\,(Overall\,Theory\,2) = P5 \wedge (P6 \vee P7) \rightarrow (P8 \wedge P9) \rightarrow (P10 \wedge P11 \wedge P12 \wedge P13)$$

The proposition put forth by this theory is that thermoeconomic management (TM) provides a novel framework for attaining sustainable business practices. This is achieved by establishing a connection between the conventional objective of profit maximization and the realities of resource depletion and environmental concerns. The location of the aforementioned point is as follows:

1. **P5 ∧ (P6 ∨ P7):** This conjunction states that the limitations of traditional approaches (P5) become more critical when considering either the value of resources highlighted by exergy (P6) or the principle of exergy conservation (P7).
2. **P8 ∧ P9:** This conjunction emphasizes the ongoing pursuit of minimizing exergy degradation (P8) as essential for achieving systemic sustainability, balancing environmental, social, technological, and economic aspects (P9).
3. **P10 ∧ P11 ∧ P12 ∧ P13):** This conjunction demonstrates the practical applications of TEM across various dimensions:
   - **P10:** Optimizing resource use and minimizing waste through exergy analysis.
   - **P11:** Informing decision-making for better resource efficiency and waste minimization, ultimately promoting sustainable business models.
   - **P12:** Fostering employee engagement in sustainability initiatives.
   - **P13:** Guiding the adoption of sustainable technologies and practices.
4. **The first implication " → "** connects the limitations of traditional approaches (P5) with the need for minimizing exergy degradation (P8 & P9). It suggests that if traditional approaches are inadequate (P5 is

true), then organizations must consider minimizing exergy degradation (P8 & P9) to achieve sustainability.

5. **The second implication " → "** connects minimizing exergy degradation (P8 & P9) with the practical applications of TM (P10-P13). It suggests that if organizations strive to minimize exergy degradation (P8 & P9), then they can leverage TM practices (P10-P13) for resource efficiency and sustainability.

T2 theory suggests that when the value of resources is assessed in terms of exergy (P6) or the concept of energy conservation (P7), the limitations of conventional profit maximization approaches (P5) become more apparent. Organizations are compelled to pursue relentless innovation and process optimization (P8) in order to achieve optimal resource utilization (P8 & P9). This is achieved by acknowledging the constraints of resources and the potential for waste minimization. By employing TEM (P10-P13), the objective of minimizing energy degradation can be effectively translated into practical applications across a range of business-related domains.

Thermoeconomic Management as a Framework for Systemic Sustainability

An integrated strategy that considers sustainability's social, technological, economic, and environmental aspects is defined as systemic sustainability (Tong et al., 2018). By recognizing the interconnectivity of these dimensions and the necessity of holistic solutions in complex situations, this approach transcends the limitations of conventional sustainability strategies (Villeneuve et al., 2017). The reduction of deleterious effects on the environment, the safeguarding of natural resources, and the mitigation of climate change are integral aspects of environmental sustainability (Pascarella & Bednar, 2021). The primary objective of economic sustainability is to achieve long-term viability and prosperity while maintaining a balance between economic growth, social progress, and environmental preservation (Borgida et al., 2022). The development and implementation of environmentally friendly technology and practices are exemplified by technological sustainability (Vacchi et al., 2024). The objective of social sustainability is to advance social justice, inclusivity, and community well-being while ensuring the equitable distribution of economic and environmental advantages throughout society (Nilsson et al., 2024).

Proposition 14 (P14): *Systemic sustainability integrates environment, economy, technology and society, recognizing their interconnectedness for holistic solutions to complex challenges.*

A framework for achieving system-wide sustainability can be established through the implementation of exergy analysis and thermoeconomic management (TM) (Walker et al., 2021). An exergetic analysis is a method of assessing the potential for useful work in energy flows. It adopts a holistic perspective that goes beyond the scope of traditional energy-saving measures (Selicati et al., 2022). By quantifying the potential for productive work in resource flows, TM draws attention to the economic and environmental consequences associated with manufacturing processes (Torres et al., 2020). The integration of environmental and economic considerations facilitates the identification of knowledge gaps and enhances comprehension (experimental analysis). By identifying the process areas where energy degradation occurs, TM facilitates the adoption of resource-saving processes and technologies (Heydari, 2022). This minimizes negative environmental impacts while providing financial benefits and cost savings (process optimization) (De Falco & Capocelli, 2020). TM encourages a comprehensive examination of energy flows throughout the product life cycle from a broad perspective. This strategy is designed to advance sustainability by integrating social, environmental, and economic considerations, including responsible sourcing practices, throughout the product life cycle, from the initial extraction of resources to the end of the product's life cycle (life cycle perspective) (Selicati et al., 2021).

Proposition 15 (P15): *Thermoeconomic management leverages exergy analysis for systemic sustainability, quantifying resource potential, optimizing processes, and integrating social & environmental factors across a product's life cycle.*

It is not uncommon for conventional management techniques to be implemented in a siloed manner, with an emphasis on the optimization of discrete departments, such as finance and production (Ghita et al., 2021). The promotion of cross-functional collaboration is a key mechanism through which TM can facilitate the dismantling of silos. It is imperative that departments including engineering, procurement, and logistics collaborate to analyze exergy flows across the value chain (Hernandez & Cullen, 2016). Moreover, system-wide optimization represents the primary focus of TM. In contrast to an emphasis on process optimization, TM encourages an understanding of the way disparate processes impact the utilization of resources and the deterioration of energy. In addition, TM incorporates sustainability into its core operations. The integration of exergy analysis and TM principles into decision-making at all levels serves to elevate sustainability from a mere standalone project to an essential component of corporate strategy (Fenerich et al., 2017).

Proposition 16 (P16): *Thermoeconomic management breaks down silos, promoting cross-functional collaboration for system-wide optimization and integrating sustainability into core business functions.*

The decision-making process surrounding the adoption of new energy-efficient technologies, including the calculation of initial expenses, can often be challenging when it comes to sustainability projects (Hrovatin et al., 2016). TM plays a pivotal role in this intricate balancing act when evaluating energy impact. It would be prudent for organizations to refrain from a total exergy drop throughout the system by conducting a thorough examination of the impact of various decisions on exergy (Huang et al., 2022). Moreover, TM illuminates synergies, the potential for alterations in one domain to engender a beneficial ripple effect in other domains (Chaturvedi et al., 2023). To illustrate, the implementation of water-saving technology may lead to a reduction in energy consumption for water treatment and water conservation, which would have a beneficial impact on both the economy and the environment.

Proposition 17 (P17): *Thermoeconomic management facilitates trade-off analysis through exergy and reveals synergies across sustainability dimensions.*

Based on the previous proposition, the following theoretical statement can be made:

$$T3\,(Overall\,Theory\,3) \;=\; P14 \;\rightarrow\; (P15 \wedge P16 \wedge P17)$$

As T3 notes, the integration of traditional, siloed management systems with the interwoven complexity of environmental, economic, technical, and social elements represents a significant paradigm shift in the pursuit of systemic sustainability. This approach, known as thermoeconomic management (TM), bridges the gap between disparate management systems and the intricate interconnections between various factors, offering a powerful framework for achieving sustainability. The location of the aforementioned is as follows:

1. **P14**: This proposition establishes the foundation—systemic sustainability requires considering the interconnectedness of environmental, economic, technological, and social aspects (environment, economy, technology, and society).
2. **P15, P16, and P17**: These propositions represent the key contributions of TM to achieving systemic sustainability:
   - **P15 (TM Leverages Exergy Analysis):** By quantifying resource potential, optimizing processes, and integrating social and environmental factors, TM provides a comprehensive approach that goes beyond traditional methods.
   - **P16 (TM Breaks Down Silos):** Traditional management often operates in silos, hindering a holistic view. TM fosters collaboration and integrates sustainability into core business functions.
   - **P17 (TM Facilitates Trade-offs and Reveals Synergies):** Sustainability decisions often involve trade-offs. TM facilitates informed choices by analyzing exergy impacts and revealing synergies across sustainability dimensions.
3. **The implication "$\rightarrow$"** in T3 signifies a logical connection based on truth values. It suggests that when systemic sustainability requires interconnectedness, TM offers a potential path toward achieving it, but doesn't guarantee success on its own.

Systemic Exergy Management (Symξx)

Propositional logic was employed as a representation of the theoretical underpinnings of thermoeconomics in connection to exergy, as indicated by the conceptual analysis conducted in the previous section (Steen & Fuenmayor, 2024). In this stage, the conceptual constructs are integrated to establish the theoretical basis for the Systemic Exergy Management (SYMΞX) approach, which serves as a framework for conducting systemic sustainability assessments.

Theoretical Contribution

SYMΞX goes beyond traditional approaches because it focuses on maximizing the usable work potential (exergy) in the processes taking place in an operating system. The theory underlying SYMΞX is presented below, using propositional logic:

$$\begin{aligned} T\_SYM\Xi X\,(Overall\,Theory) = {} & (P1 \wedge P2) \wedge (P5 \wedge P6) \\ & \rightarrow (P8 \wedge P9 \wedge P14) \\ & \rightarrow (P15 \wedge P16 \wedge P17 \wedge P3 \\ & \quad \wedge P4) \end{aligned}$$

Explanation:

1. **Synergy from Thermoeconomics (P1 and P2):** SYMΞX builds upon the holistic approach of thermoeconomics (P1) with a focus on understanding resource flows through exergy analysis (P2). This synergy is crucial for achieving the following outcomes.

2. **Optimizing for Sustainability (P5 and P6):** SYMΞX acknowledges the limitations of traditional profit maximization (P5) and emphasizes exergy as a tool to optimize resource use (P6), promoting sustainability and responsible resource management.
3. **Minimizing Exergy Degradation (P8 and P9):** SYMΞX prioritizes continuous innovation and process optimization (P8) to minimize exergy degradation, leading to maximized resource utilization and systemic sustainability (P9) that considers environmental, social, technological, and economic aspects.
4. **Systemic Transformation through SYMΞX (P15, P16, P17):** By leveraging exergy analysis, SYMΞX facilitates:
    a. Quantifying resource potential, optimizing processes, and integrating social & environmental factors across a product's life cycle (P15).
    b. Breaking down silos and promoting cross-functional collaboration, integrating sustainability into core business functions (P16).
    c. Analyzing trade-offs and revealing synergies across sustainability dimensions (P17).
5. **Sustainable Business Transformation (P3 and P4):** Ultimately, SYMΞX fosters innovation in product design, manufacturing, and supply chain management (P3), leading to the transformation of business management through metrics that capture resource efficiency and incentivize sustainability practices (P4).
6. **The first implication " → "** If both P1 and P2 are true (synergy from thermoeconomics), and both P5 and P6 are true (optimizing for sustainability), then P8, P9, and P14 must also be true (minimizing exergy degradation and achieving systemic sustainability).
7. **The second implication " → "** If P8, P9, and P14 are true (minimizing exergy degradation and achieving systemic sustainability), then P15, P16, P17, P3, and P4 must also be true (systemic transformation and sustainable business practices).

In the following text, the authors present their opinions and knowledge regarding the potential of SYMΞX in the field of management science. In the corporate domain, SYMΞX can act as a catalyst for systemic sustainability by offering a robust theoretical framework that helps overcome the limitations of traditional models. In essence, SYMΞX represents a paradigm shift from the conventional profit-centric approach (Dyck et al., 2023) of thinking with a value-for-money approach (Karikari Appiah et al., 2022). He acknowledges the potential risks associated with an emphasis on immediate financial gain, which can lead to detrimental long-term consequences. Instead, he advocates for an incentive-based approach that encourages sustainable practices. The aforementioned change encourages organizations to optimize resource efficiency by fine-tuning their processes. To mitigate energy losses, SYMΞX also advocates for continuous innovation and development. This underscores the importance of continuous evaluation and development, motivating companies to refine and strengthen their procedures to prevent resource depletion and reduce their environmental impact. Furthermore, SYMΞX mitigates operational impediments and cultivates collaboration through the integration of sustainability into foundational corporate strategies and the promotion of interdepartmental cooperation. Furthermore, SYMΞX is adept at facilitating well-informed decision-making through comprehensive trade-off analysis, which is an additional crucial characteristic. SYMΞX provides companies with the data and resources necessary to make informed decisions regarding emission reduction, as it can quantify the impact of emissions and comprehending the interactions between various sustainability factors. SYMΞX advocates for an all-encompassing approach that considers the intricate interplay between social, technological, economic, and environmental considerations. SYMΞX places a premium on the optimization of resources, which serves to advance technical growth, environmental health, and economic stability.

A concise overview of the Systemic Exergy Management (SYMΞX) conceptual framework can be found in Table 3. The theoretical framework is based on the complementary nature of thermoeconomics and exergy analysis, which together provide the fundamental ideas and constituent parts of this methodology. The SYMΞX methodology is designed to achieve a number of key objectives, including the optimization of sustainability, the minimization of energy degradation, and the realization of systemic transformation. The fundamental tenets underscore the necessity for resource optimization, continuous innovation and enhancement, interdepartmental collaboration, sustainable corporate transformation, and comprehensive trade-off analysis to facilitate well-informed decision-making. The anticipated results of this methodology are a catalyst for systemic sustainability, a shift in mentality away from profit-centeredness to prioritize resource efficiency, ongoing innovation to lessen the impact on the environment and degradation of resources, cooperative efforts to incorporate sustainability into business strategies, and well-informed decision-making through trade-off analysis. To advance sustainability and foster environmental health, economic stability, and technology advancement for a sustainable future, SYMΞX encourages a holistic approach that acknowledges the interplay between environmental, economic, technical, and social variables.

Table 3 Interconnected elements of systemic exergy management (SYMΞX)

Theoretical foundations		
Thermoeconomics (P1) + Exergy analysis (P2)		
Core principles	Key components	Goals
Synergy from Thermoeconomics (P1 and P2)	Resource optimization	Maximize resource efficiency
Optimizing for Sustainability (P5 and P6)	Perpetual innovation and enhancement	Minimize exergy
Minimizing Exergy Degradation (P8 and P9)	Ongoing assessment and advancement	Degradation
Systemic Transformation through SYMΞX (P15, P16, P17)	Interdepartmental Collaboration	Promote systemic
Sustainable Business Transformation (P3 and P4)	Comprehensive Trade-off analysis	Sustainability
	Informed decision-making	Foster technological Advancement
		Advance Environmental health and economic Stability
		Complexity
		Organizational flexibility
Outcomes		
Catalyst for systemic sustainability: SYMΞX surpasses conventional models, prioritizing resource optimization over immediate financial gains		
Shift in mindset: Moves away from profit-centric thinking to prioritize resource efficiency		
Continuous innovation: Advocates for ongoing improvement to reduce resource depletion and environmental impact		
Collaborative efforts: Dismantles operational silos, integrates sustainability into business strategies, and fosters interdepartmental cooperation		
Informed decision-making: Equips organizations with tools for comprehensive trade-off analysis to diminish overall exergy degradation		
Holistic approach: Acknowledges interplay between environmental, economic, technological, and social factors		
Advancing sustainability: Promotes environmental health, economic stability, and technological advancement for a sustainable future		

Theoretical Framework

Considering the aforementioned concepts and principles derived from abductive inference, we can now propose the postulates that serve as the foundation for the new theory of Systemic Exergy Management (SYMΞX).

1. **|PS1| Thermoeconomic Foundation:** The fundamental ideas of thermoeconomics provide a comprehensive understanding of the utilization of resources within organizational contexts. This approach elucidates the physical principles that govern energy transitions and the economic consequences of resource utilization by integrating thermodynamics with economic analysis.
2. **|PS2| Systemic Sustainability:** The functioning of businesses is contingent upon the existence of intricate structures, which are characterized by the interconnectivity of various social, technical, economic, and environmental elements. Long-term success necessitates an acknowledgment of the impact of organizational actions across these various dimensions. Organizations are responsible for managing systemic sustainability, ensuring that their actions are aligned with the broader objectives and guided by thermoeconomic principles.
3. **|PS3| Resource Optimization:** In contrast to profit-centric approaches, organizations prioritize the optimization of resources throughout the value chain. By minimizing environmental impact and ensuring long-term viability, organizations foster sustainable resource utilization practices through the use of thermoeconomic analysis.
4. **|PS4| Exergy Analysis as a Core Tool:** An essential indicator of the potential utilization of resources in a work environment is its exergy, which serves as the foundation for effective resource management. By employing exergy analysis based on thermal economic principles, organizations can identify inefficiencies in resource consumption and prioritize measures that optimize resource value. This enables them to establish a sustainable trajectory through the design of more efficient resource management strategies.
5. **|PS5| Continuous Improvement and Innovation:** It is imperative for organizations to consistently enhance their environmental practices and resource efficiency, given the ever-evolving nature of sustainability concerns. Organizations that espouse an innovative culture engage in the investigation of novel technologies and procedures that prevent the

deterioration of resources and ensure continued advancement.

6. **|PS6| Holistic Decision-Making:** Organizations employ an all-encompassing approach to decision-making that extends beyond the conventional economic criteria. The incorporation of environmental and social considerations into decision-making frameworks ensures the formulation of ethical and sustainable decisions, informed by thermoeconomic principles that take into account the long-term consequences of decisions.
7. **|PS7| Cross-Functional Collaboration:** The existence of organizational silos presents a significant challenge in comprehending the utilization of resources and the sustainability initiatives that are in place across the entire organization. Organizations that facilitate cross-functional collaboration are better positioned to integrate sustainability principles into all business operations, fostering alignment and synergies toward shared sustainability objectives.
8. **|PS8| Data-Driven Management:** Despite the growing emphasis on data-driven decision-making, intuition remains an important aspect of organizational decision-making processes. The use of sustainability indicators based on thermoeconomic concepts can provide deeper insights, facilitating well-informed decision-making and efficient sustainability operations.
9. **|PS9| Systemic Transformation:** Organizations seek to accelerate systemic transformation because they recognize the cumulative impact of their activities. An organization may facilitate change beyond its own boundaries by advocating for sustainable practices across the supply chain and broader environment, thereby advancing sustainability as a whole.
10. **|P10| Long-Term Perspective:** In contrast to those who are shortsighted in their success, corporations adopt a long-term perspective. In light of the impact of organizational actions on future generations, and in alignment with thermoeconomic principles, organizations demonstrate a robust commitment to sustainable resource utilization, ensuring long-term sustainability and success.

These postulates explicitly situate thermoeconomics at the core of SYMΞX, within the context of organizational theories. By employing exergetic analysis, organizations can make well-informed decisions that optimize resource use, minimize impacts on the environment and society, and contribute to the achievement of long-term systemic sustainability. Based on the aforementioned postulates, a conceptual framework of Systemic Exergy Management (SYMΞX) was constructed using graph theory. Each postulate (PS 1 ÷ PS 10) is represented as a node, and the relationships between these postulates are represented as arcs connecting them (Fig. 2).

Relationships between postulates (arcs) are identified and described below:

- **PS1 → PS2 and PS3:** Thermoeconomic principles provide the foundation for both systemic sustainability (PS2) and resource optimization (PS3). They inform the understanding of environmental and economic implications (PS2) and guide the optimization of resource use (PS3).
- **PS2 → PS6:** Achieving systemic sustainability (PS2) necessitates holistic decision-making (PS6). This requires considering environmental and social consequences alongside economic factors.
- **PS3 → PS4:** Resource optimization (PS3) is facilitated by exergy analysis (PS4). By quantifying usable work potential, exergy analysis identifies inefficiencies in resource use, aiding optimization efforts.
- **PS4 → PS5:** Exergy analysis (PS4) informs continuous improvement and innovation (PS5). Understanding inefficiencies revealed by exergy analysis fuels the search for new technologies and processes that minimize resource degradation.
- **PS5 & PS7 → PS3:** Both continuous improvement (PS5) and interdepartmental collaboration (PS7) contribute to resource optimization (PS3). Innovation and collaboration lead to better resource management practices.
- **PS6 and PS8 → PS9:** Holistic decision-making (PS6) and data-driven management (PS8) are crucial for systemic transformation (PS9). By considering all factors and leveraging data, organizations can influence sustainable practices beyond their boundaries.
- **PS7 and PS8 → PS6:** Interdepartmental collaboration (PS7) and data-driven management (PS8) facilitate holistic decision-making (PS6). Collaboration ensures diverse perspectives are included, and data provides the foundation for informed choices.
- **PS2, PS3, PS5, PS6, PS8, and PS9 → PS10:** All these postulates (PS2, PS3, PS5, PS6, PS8, & PS9) contribute to a long-term perspective (PS10). By focusing on sustainability, resource optimization, and ethical decision-making, organizations ensure long-term viability.
- **PS10 → PS3:** A long-term perspective (PS10) reinforces resource optimization (PS3). By considering intergenerational impacts, organizations prioritize sustainable resource use practices.

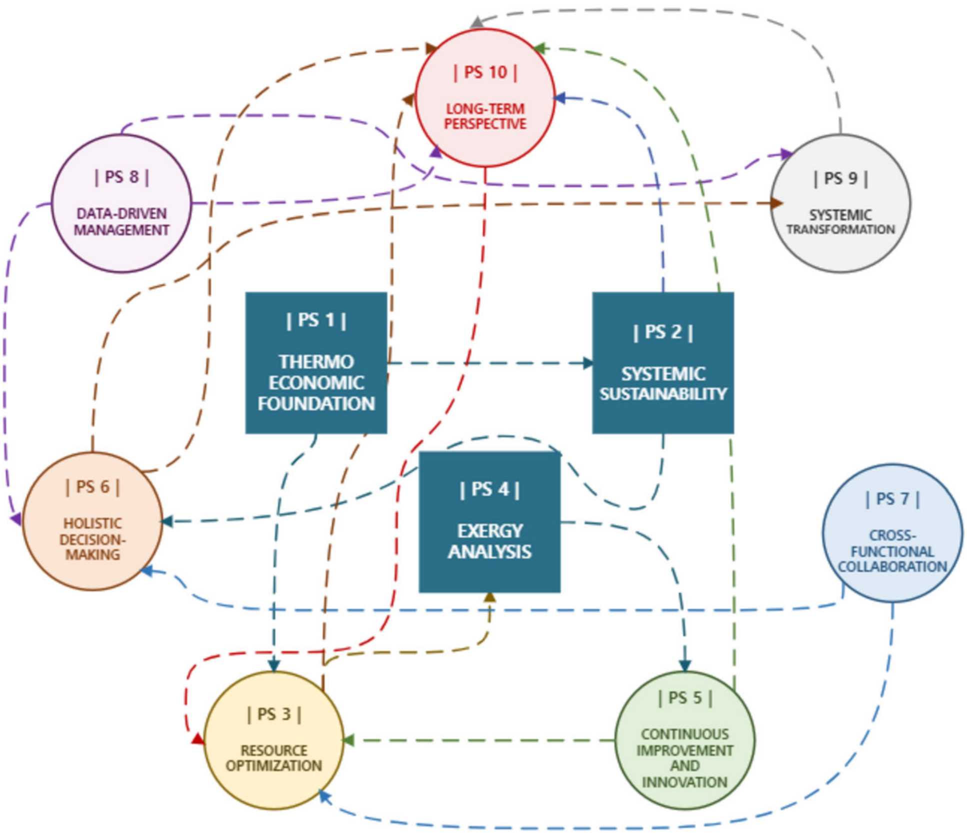

Fig. 2 Conceptual Framework of Systemic Exergy Management (SYMΞX) based on Graph Theory

Mathematical Framework

Figure 2 presents a graph-based conceptual framework that illustrates Systemic Exergy Management (SYMΞX) as a holistic theory with a robust foundation in thermoeconomics. The framework elucidates the interconnection between resource optimization, data-driven decision-making, cross-functional collaboration, and a long-term perspective. In light of the aforementioned postulates and relationships, a proposed description of the SYMΞX model is presented, employing a set of mathematical functions.

Setup:

- **Resources (R):** $R = \{r_1, r_2, \ldots, r_n\}$ (where r_i represents a specific type of resource, e.g., raw material, energy source)
- **Processes (P):** $P = \{p_1, p_2, \ldots, p_m\}$ (where p_i represents a specific process within the value chain, e.g., manufacturing, transportation)
- **Decisions (D):** $D = \{d_1, d_2, \ldots, d_n\}$ (where d_i represents a specific decision with potential outcomes, e.g., investment in new technology)
- **Impacts (I):** *I = {I_env, I_social, I_economic, I_tech}* (where *I_env* represents environmental impact, *I_social* represents social impact, *I_economic* represents economic impact, and *I_tech* represents technological impact)
- **Metrics (M):** *M = {M_exergy, M_efficiency, M_cost, M_sustainability}* (where *M_exergy* represents exergy content, *M_efficiency* represents resource use efficiency, *M_cost* represents economic cost, and *M_sustainability* represents a composite systemic sustainability score)

Functions:

(i) Exergy analysis (EA): R → real number

$$EA(r\_i) = \Sigma(x\_j * exergy\_content(j, state(r\_i)))$$

where:

- *i* refers to the specific resource (*r_i*)
- *j* refers to each component within the resource (e.g., chemical elements in a material)
- *x_j* represents the mass or volume fraction of component j within *r_i*
- exergy_content(j, state(*r_i*)) is a pre-defined function that retrieves the exergy content per unit of component j based on its thermodynamic state (e.g., temperature, pressure) obtained from state(*r_i*))

  This function calculates the exergy content of a resource, representing its usable work potential.

(ii) Resource optimization (RO): P x R → R'.
This function identifies the optimized state of a resource for a specific process, minimizing exergy degradation.

$$RO(p\_j, r\_i) = minimize\,(\Delta EA(r\_i, p\_j))$$

where:

- *j* refers to the specific process (*p_j*)
- *i* refers to the specific resource (*r_i*)
- *ΔEA(r_i, p_j) = EA(r_i')—EA(r_i)* represents the change in exergy content after applying process *p_j* to resource *r_i,* resulting in the optimized resource state *r_i*')

(iii) Sustainability assessment (SA): D x I → Real Number
This function calculates a sustainability score for a decision, considering its environmental, social, economic, and technological impacts.

$$SA(d\_k, I\_l) = w\_l * f\_impact(d\_k, I\_l)$$

where:

- *k* refers to the specific decision (*d_k*)
- *l* refers to the specific impact category (*I_l*)—environmental, social, or economic
- *w_l* represents the weight assigned to impact category *l*, reflecting its relative importance (weights can be determined based on organizational priorities or industry standards)
- *f_impact(d_k, I_l)* is a pre-defined function that quantifies the impact of decision *d_k* on impact category *I_l*. This function can involve various metrics and calculations depending on the specific impact being assessed (e.g., life cycle assessment for environmental impact, social impact assessment metrics for social impact, and economic cost calculations)

(iv) Holistic decision-making (HDM): D x M -> D'
This function selects the most sustainable and cost-effective decision option by balancing economic cost and a composite sustainability score.

$$HDM(d\_k, M) = \arg\max\,(h(M\_\cos t(d\_k), M\_sustainability(d\_k)))$$

where:

- *k* refers to the specific decision (*d_k*)
- *M = {M_exergy, M_efficiency, M_cost, M_sustainability}* represents the set of relevant metrics
- *h represents a weighting function. Its purpose is to combine the economic cost (M_cost(d_k)) and the composite sustainability score (M_sustainability(d_k)) into a single value that can be used to compare different decision options (d_k).*
- *M_cost(d_k)* is a function that calculates the economic cost associated with decision *d_k*
- *M_sustainability(d_k) = Σ (w_l * SA(d_k, I_l))* is a composite sustainability score for decision *d_k*, calculated

(xxii) Integration of long-term perspective
The long-term perspective can be incorporated into the model by introducing discounting factors into the economic cost function (M_cost). Discounting future costs reflects the time value of money and prioritizes current investments with long-term benefits. The discount rate would need to be carefully chosen, balancing immediate financial considerations with long-term sustainability goals. The economic cost function (*M_cost)* could be modified as follows

$$M\_\cos t(d\_k) = immediate\_\cos t(d\_k) + \Sigma\,[f(discount\_rate, year\_i) * future\_\cos t(d\_k, year\_i)]$$

where:

- *immediate_cost(d_k)* represents the immediate economic cost of decision *d_k*. Represents the immediate economic cost of decision d_k (e.g., investment cost).
- *future_cost(d_k, year_i)* represents the economic cost of decision *d_k* in year *i*. This could include factors like resource depletion costs, maintenance costs of long-lived assets, or potential liabilities arising from environmental or social consequences.
- *f(discount_rate, year_i)* is a year-specific discounting factor based on the chosen discount rate, decreasing the weight of future costs as time goes on.

Relationships:

1. **RO(P, EA(R)) = R':** The optimized resource state (R') is achieved by applying the resource optimization function (RO) that utilizes exergy analysis (EA) to minimize exergy degradation for each process-resource combination.
2. **SA(D, I) influences HDM(D, M):** The sustainability assessment (SA) provides the sustainability score

(M_sustainability) as an input for the holistic decision-making function (HDM).

3. **HDM(D, M) considers PS1 (Thermoeconomic Foundation):** The function (h) used in HDM can incorporate a factor that reflects the economic value of the exergy content (M_exergy) derived from the resource analysis (EA), aligning with thermoeconomic principles.
4. **Long-term perspective (PS10) influences D:** Decision options (D) can be evaluated using the Economic Cost Function (M_cost) that consider intergenerational impacts, reflecting a long-term perspective.

Central to the SYMΞX model is the complex interplay between four key relationships; a more extensive discussion of these relationships is provided below.

1. **Resource optimization (RO) driven by exergy analysis (EA):** This relationship forms the foundation for efficient resource utilization. By leveraging exergy analysis (*EA*), which quantifies a resource's usable work potential, organizations can identify the most optimized state (*R'*) for each resource (*R*) within a specific process (*P*). Minimizing exergy degradation through *RO* ensures that resources are used effectively, reducing waste and maximizing their value throughout the value chain.
2. **Systemic sustainability assessment (SA) informing holistic decision-making (HDM):** This relationship ensures that environmental, social, economic, and technological considerations are woven into the fabric of decision-making. The sustainability assessment (*SA*) provides a holistic score (*M_sustainability*) that reflects the impact (*I*) of a decision (*D*) across all these crucial dimensions. This score, along with economic cost information (*M_cost*), feeds into the holistic decision-making function (*HDM*). *HDM* then prioritizes options that not only deliver economic benefits but also contribute to a sustainable future.
3. **Thermoeconomic foundation (PS1) shaping HDM:** This relationship ensures that economic considerations are intertwined with the laws of thermodynamics. The function (*h*) used in *HDM* can incorporate a factor that reflects the economic value of the exergy content (*M_exergy*) derived from the resource analysis (*EA*). This aligns with the fundamental principles of thermoeconomics, where resource utilization is optimized considering both its physical properties and economic viability.
4. **Long-term perspective (*PS10*) influencing decision-making (*D*):** This relationship ensures that decisions are not driven solely by short-term gains. The Long-Term Perspective principle (*PS10*) is reflected in the economic cost function (*M_cost)*. By considering intergenerational impacts and incorporating future costs (discounted based on a chosen rate), decision options (*D*) are evaluated with a long-term lens. This ensures that decisions made today contribute to a sustainable future for generations to come.

This model provides a mathematical framework for elucidating the fundamental concepts underlying SYMΞX. The model permits the quantitative examination of resource consumption, decision-making processes, and the implications of sustainability by employing functions and sets. It may be expanded by incorporating precise mathematical formulae or optimization algorithms for decision-making and resource management, tailored to specific use scenarios. SYMΞX proposes that decisions be made with a long-term vision in mind, taking into account economic viability, sustainability in its various forms, and resource efficiency. Organizations may utilize this interwoven web of ties to facilitate the decision-making process in a manner that is supportive of sustainability.

Contribution to the Development of Management Theories

In comparison to conventional management theories, Systemic Exergy Management (SYMΞX) represents a pioneering approach to sustainability management. The primary objectives of conventional theories of productivity enhancement are the establishment of a hierarchical structure, the optimization of efficiency, and the standardization of norms (Borim-de-Souza et al., 2020). These concepts have been pivotal in shaping the discourse on organizational responsibility; however, they have also been subject to critique for their failure to adequately address the impact of organizational actions on society and the environment.

Neoclassical Economics

Friedman's theory places emphasis on profit maximization and shareholder dominance, which can potentially encourage unsustainable behavior (Neck, 2022). SYMΞX challenges the aforementioned idea by promoting a global strategy that considers the interdependence of environmental, economic, technical, and social factors. This guarantees that businesses can maintain economic viability while operating within the ethical limits of the environment and society..

Scientific Management

This is a seminal theory of management, first proposed by Frederick Taylor. The objective is to enhance efficiency by employing a scientific approach to the analysis of work processes (Hill & Van Buren, 2018). The approach emphasizes standardization, specialization and the division of labor, with the overarching objective of maximizing productivity and minimizing costs. In contrast to the principles of scientific management, SYMΞX places a greater emphasis on sustainability. While scientific management is primarily concerned with enhancing productivity, SYMΞX integrates the tenets of thermoeconomics and exergetic analysis to optimize the utilization of resources and minimize environmental impact. Additionally, SYMΞX underscores the significance of long-term resilience and ethical decision-making, which are not central tenets of scientific management.

Administrative Management

The theory was developed by Henri Fayol and is centered on organizational structure and managerial functions (Pataki & Sagi, 2009). The five key managerial responsibilities are as follows: planning, controlling, commanding, coordinating, and organizing. The theory prioritizes a hierarchical structure and clear lines of authority with the objective of improving efficiency and fostering cooperation within the company. SYMΞX's incorporation of systemic principles of sustainability into management processes represents a more comprehensive approach than that of administrative management, which primarily focuses on coordination and organizational structure. The focus of administrative management is on the internal workings of the company, whereas SYMΞX considers the environmental and social aspects of the business. SYMΞX's management strategy is characterized by an emphasis on resource efficiency and system sustainability, which facilitates a more comprehensive approach to organizational management.

Bureaucracy

In this theory, Weber directs attention to standardized procedures and hierarchical structures that may contribute to rigidity and impede adaptability to sustainability problems (Sager & Rosser, 2021). In contrast, SYMΞX fosters creativity and continuous improvement. Such an approach encourages the development of a culture of adaptation and flexibility, which enables businesses to continually enhance their systemic sustainability measures and resource efficiency.

Human Relations Theory

The theory was initially proposed by Mayo, who developed it in response to the perceived shortcomings of scientific and administrative management theories (Bruce & Nyland, 2011). The theory underscores the pivotal role of social variables, worker happiness, and motivation. Furthermore, it encourages open communication, employee well-being, and participatory decision-making, underscoring the significance of interpersonal connections and the human aspect of business. Although human relations theory acknowledges the role of social elements in organizational efficiency, it does not address sustainability challenges in any specific manner. In contrast, SYMΞX acknowledges the interconnection between corporate actions and social and environmental consequences by integrating human and social capital into managerial strategies. SYMΞX endorses the principles of social resource efficiency, creativity, and teamwork, which are aligned with the objectives of sustainable management.

Agency Theory

The primary focus of agency theory is the analysis of the relationship between principals and agents within an organizational context. This field of study also places significant emphasis on the mitigation of conflicts of interes (Eisenhardt, 1989). While agency theory places an emphasis on coordinating incentives and oversight procedures to reduce agency issues, SYMΞX places a higher priority on efficacy than efficiency. SYMΞX provides a more comprehensive perspective than the agency relationship by integrating concepts from thermoeconomics and exergetic analysis to optimize resource utilization and minimize environmental impact.

Theory of Value

The primary objective of value theory (Pirgmaier, 2021) is the creation and capture of value, frequently through competitive advantage, innovation, and consumer value propositions. In contrast to the primacy of morality and sustainability in decision-making, value theory prioritizes the generation of value and the attainment of competitive advantage. Although both theories aim to enhance organizational performance, SYMΞX adopts a more comprehensive strategy by integrating principles of systemic sustainability into business models.

Transaction Cost Theory

The costs associated with interactions between individuals or organizations are examined by transaction cost theory, along with the governance systems that may be employed to reduce these costs (Cuypers et al., 2021). The objective of transaction cost theory is to enhance efficiency and reduce costs by optimizing transactional procedures and governance frameworks. In contrast, SYMΞX places a greater emphasis on sustainability, pursuing optimization of resources, reduction of environmental impact, and a commitment to ethical decision-making and long-term resilience (De Marchi et al., 2023).

Schumpeterian Theory

The Schumpeterian theory (Emami Langroodi, 2017) elucidates the role of entrepreneurship and innovation in propelling economic growth and organizational transformation. SYMΞX is predicated on the principles of resource efficiency and technical innovation. In contrast, Schumpeterian theory underscores the pivotal role of innovation and creative destruction in organizational dynamics. The two theories both emphasize innovation, but they do so in different ways. While Schumpeterian theory places greater emphasis on economic development, SYMΞX places a higher priority on systemic sustainability.

Stakeholder Theory

In accordance with the tenets of stakeholder theory, it is incumbent upon companies to consider the interests of all stakeholders while making decisions (Mahajan et al., 2023). While SYMΞX espouses a life cycle strategy to engage stakeholders in the value chain, stakeholder theory places greater emphasis on stakeholder management and the broader social implications of organizational actions. Although both theories espouse a more comprehensive approach to organizational decision-making, SYMΞX places particular emphasis on systemic sustainability.

Systemic Theory

The systemic theory of thought posits that organizations are complex systems that interact with their surroundings and are comprised of interdependent components that are themselves part of a larger systemic framework (Amagoh, 2016). SYMΞX shares the systemic school's recognition of the interconnection between organizational components and their broader environmental context. Although the systemic school provides a comprehensive framework for understanding organizational complexity, SYMΞX offers specific guidelines and tools for optimizing resource efficiency and minimizing environmental impact in organizational systems.

Resource-Based View

In accordance with the tenets of the resource-based theory, the distintive and valued resources and capabilities of a corporation serve as the foundation for its competitive advantag (Davis & DeWitt, 2021). The resource-based theory is concerned with the utilization of an organization's internal resources and competencies, frequently through the consolidation of resources and the strategic allocation of assets, in order to gain a competitive advantage. SYMΞX, in contrast, places greater emphasis on the optimization and sustainability of resources, with a particular focus on resource efficiency and the reduction of environmental impact. While both theories acknowledge the relevance of organizational resources, resource-based theory places greater emphasis on competitive advantage, whereas SYMΞX prioritizes environmental sustainability.

To compare SYMΞX with classical organizational theories, we can visualize their key features and distinguishing characteristics in a comparative chart (Table 4).

The visual representation serves to elucidate the pioneering contributions of Systemic Exergy Management (SYMΞX) to the domain of sustainability management. To this end, it compares and contrasts the principles and approaches espoused by SYMΞX with those of classical organizational theories.

Enhancing Organizational Flexibility Through SYMΞX

The conventional approach to organizational flexibility has been to adapt to changing consumer preferences and market circumstances. However, the imperative of addressing sustainability concerns necessitates a more comprehensive definition that incorporates environmental considerations. One useful framework for enhancing this adaptability is provided by Systemic Exergy Management (SYMΞX).

SYMΞX employs exergy analysis to identify opportunities for reducing resource utilization and waste generation, thereby reducing reliance on specific resources and enhancing flexibility in response to price fluctuations. Furthermore, SYMΞX advocates the selection of suppliers based on the exergy content of their products, thereby expanding the pool of suppliers and mitigating the associated risks of excessive dependence. Furthermore, SYMΞX facilitates process adaptation. It allows businesses to optimize energy inefficiencies in manufacturing processes, thereby enhancing their flexibility in responding to environmental regulations or fluctuating energy prices. Moreover, SYMΞX concepts have inspired the development of environmentally friendly technology with the objective of reducing exergy breakdown. This encourages

Table 4 Visual representation comparing Systemic Exergy Management (SYMΞX) with classical organizational theories

Theory	Key features	New contribution to sustainability management
Neoclassical economics	Emphasizes shareholder supremacy and profit maximization Often leads to unsustainable practices	Challenges the notion of shareholder supremacy Advocates for a holistic approach considering environmental, economic, technological, and social aspects
Scientific management	Focuses on efficiency through scientific analysis of work processes Emphasizes standardization, specialization, and division of labor	Prioritizes sustainability over efficiency Integrates principles of thermoeconomics and exergetic analysis for resource optimization
Administrative management	Focuses on organizational structure and management functions Emphasizes hierarchical structure and clear lines of authority	Takes a broader perspective, integrating systemic sustainability principles into management practices Considers external environmental and social impacts
Bureaucracy	Focuses on hierarchical structures and standardized processes Can create rigidity, hindering adaptation to sustainability challenges	Promotes continuous improvement and innovation for flexibility and adaptability Fosters a culture of systemic sustainability practices
Human relations	Emphasizes social factors, employee motivation, and satisfaction Advocates participatory decision-making and open communication	Promote human and social capital into management practices Promotes social resource efficiency, innovation, and collaboration
Agency theory	Focuses on mitigating conflicts of interest between principals and agents Emphasizes aligning incentives and monitoring mechanisms	Prioritizes effectiveness over efficiency Integrates principles from thermoeconomics and exergetic analysis
Theory of value	Centers on value creation and competitive advantage Emphasizes innovation, customer value propositions, and organizational change	Prioritizes sustainability and ethical decision-making over competitive advantage Integrates systemic sustainability principles into innovative business model
Transaction cost theory	Examines costs associated with transactions and governance mechanisms Focuses on optimizing transactional processes to reduce costs	Prioritizes sustainability by minimizing environmental impact Emphasizes long-term resilience and ethical decision-making
Schumpeterian theory	Emphasizes innovation and entrepreneurship as drivers of growth and change Highlights creative destruction in organizational dynamics	Focuses on technological innovation and resource optimization Prioritizes systemic sustainability over economic growth
Stakeholder theory	Suggests considering interests of all stakeholders in decision-making Emphasizes stakeholder management and societal impact of decisions	Advocates for a broader perspective on organizational decision-making Focuses on a life cycle approach to engage stakeholders in the value chain
Systemic theory	Views organizations as complex systems interacting with environments Emphasizes interdependence of organizational elements and systemic context	Recognizes interconnectedness of organizational elements and environmental context Offers specific principles and tools for sustainability practices
Resource-based view	Suggests competitive advantage based on unique and valuable resources Focuses on leveraging internal resources for competitive advantage	Prioritizes systemic sustainability and resource optimization Emphasizes effective use of resources and minimizing environmental impact

creativity and facilitates the development of solutions to environmental challenges that will emerge in future. In addition to promoting operational and financial adaptability, SYMΞX also encourages stakeholder adaptability. Furthermore, it encourages the participation of stakeholders by integrating environmental concerns into core business operations. This open and cooperative approach enables businesses to adapt to evolving stakeholder expectations regarding environmental responsibility. Furthermore, SYMΞX facilitates the development of collaborative sustainability solutions through partnerships with key stakeholders, including suppliers, customers, and communities. This collaborative approach enhances a company's ability to navigate complex environmental challenges through collective action.

At last, SYMΞX transcends conventional resource management, thereby providing companies with greater general adaptability. The promotion of resource efficiency, process optimization, and stakeholder involvement enables SYMΞX to facilitate the adaptation and flourishing of businesses in the context of mounting environmental limitations. The long-term success and viability of an organization are contingent upon this enhanced flexibility.

Discussion and Limitations

This study introduces the Systemic Exergy Management (SYMΞX) framework as a novel theoretical model that integrates thermoeconomic principles into business performance measurement. By employing exergy analysis, SYMΞX presents a comprehensive methodology for evaluating organizational performance that transcends the limitations of conventional financial metrics. It incorporates considerations of resource efficiency, environmental impact, and social responsibility, offering a more holistic and multifaceted approach to assessing organizational impact. The framework's capacity to align business decisions with both economic and environmental imperatives enhances organizational flexibility, enabling companies to more effectively adapt to resource scarcity and evolving environmental regulations. In this context, SYMΞX makes a significant contribution to the field of business scholarship, addressing shortcomings in performance measurement systems and promoting advances in sustainability practices.

The practical implications of SYMΞX are of considerable consequence. Organizations that adopt this framework are able to develop comprehensive Sustainability Performance Indicators (SPIs) that reflect not only financial outcomes, but also technological, environmental, and social dimensions. The integration of these indicators into performance measurement allows companies to demonstrate a deeper commitment to corporate responsibility, thereby improving stakeholder trust and reputation. The SYMΞX framework integrates exergy analysis into business performance measurement, providing a holistic perspective on organizational impact. Furthermore, it advances flexible systems management by aligning corporate decision-making with both financial and ecological imperatives, thereby enhancing organizational flexibility in response to resource scarcities and environmental regulations. SYMΞX plays a pivotal role in advancing flexible systems management by offering a framework that adapts to dynamic sustainability challenges through the lens of exergy efficiency. SYMΞX enhances organizational flexibility by aligning corporate decision-making with both financial and ecological imperatives, thereby enabling businesses to respond to resource scarcities and environmental regulations. Recent studies (Ma et al., 2022; A. Singh et al., 2023; S. Singh et al., 2021a, b) highlight the necessity for flexible, data-driven management models that integrate environmental considerations. SYMΞX addresses this gap through its multi-dimensional sustainability assessment.

While the SYMΞX framework offers several advantages, it is not without its own inherent limitations. Firstly, the framework's reliance on thermoeconomic principles, particularly exergy analysis, may prove challenging for industries lacking the requisite technical expertise in thermodynamics. The complexity of exergy calculations may impede the framework's adoption, particularly in sectors where environmental metrics are not yet fully integrated into decision-making processes. Moreover, SYMΞX has not yet been subjected to comprehensive empirical validation across a range of industrial sectors. The extent to which it can be applied in addressing sector-specific sustainability challenges remains an open question that requires further investigation. Moreover, while SYMΞX offers a robust theoretical framework, the translation of its principles into actionable, user-friendly decision-making tools for businesses may prove challenging. In light of the inherent complexities of thermoeconomics, it is imperative that future endeavors prioritize the accessibility of SYMΞX to a broader business community, including small- and medium-sized enterprises. It is imperative that researchers investigate methods to streamline exergy analysis for practical applications. This could be achieved by developing decision-support software or tools that integrate SYMΞX with existing management systems. Furthermore, additional research is required to examine the integration of SYMΞX with global reporting frameworks, such as the European Sustainability Reporting Standards (ESRS), and to ascertain how it can enhance existing sustainability management systems.

Conclusion

This study introduces the Systemic Exergy Management (SYMΞX) framework, which represents a pioneering model that integrates thermoeconomic principles into business performance measurement. SYMΞX offers a comprehensive approach to sustainability, encompassing not only financial outcomes but also resource efficiency, environmental impact, and social responsibility. By employing exergy analysis, this framework facilitates a more profound comprehension of an organization's comprehensive impact, thereby enabling more judicious decision-making that strikes a balance between profitability and sustainability objectives. The SYMΞX framework contributes to the advancement of business science by filling gaps in traditional performance assessment methods and providing a flexible, adaptable model for addressing contemporary sustainability challenges. The framework assists organizations in aligning their operations with both financial and environmental objectives, thereby enhancing organizational flexibility and resilience in response to environmental regulations and resource constraints. In future, research should focus on empirically validating SYMΞX across different industries to test its versatility in different contexts. Moreover, the creation of user-friendly instruments for incorporating SYMΞX into routine business operations will be vital to enhancing its practical implementation. The path to systemic sustainability necessitates the implementation of frameworks such as SYMΞX, which serve to direct organizations toward the adoption of more ethical and resource-efficient practices. Adoption of the SYMΞX framework enables companies to make a significant contribution to a sustainable future while maintaining competitiveness and financial success.

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Declarations

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Key Questions

1. What are the limitations of traditional economic models in considering resource efficiency and environmental impact in corporate performance assessments?
2. How can the integration of thermoeconomic principles bridge the existing gaps in corporate performance evaluation models?
3. What are the theoretical and practical challenges in applying exergy analysis as a measure of resource efficiency in organizations?
4. How can the SYMΞX framework contribute to a more comprehensive understanding of systemic sustainability compared to current approaches?
5. What are the implications of adopting the SYMΞX framework for organizational flexibility and adaptation to evolving economic and environmental conditions?
6. What gaps exist in the current literature regarding the use of exergy as a sustainability performance indicator, and how can the SYMΞX framework address them?

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CHAPTER III - SOCIAL LIFE CYCLE ASSESSMENT IN INDUSTRY 5.0

This third article completes the integrative vision of systemic sustainability by systematically and rigorously addressing the social dimension, a dimension that has historically received less academic and methodological attention than the environmental and economic pillars. In the contemporary era of Industry 5.0, characterized by the integration of advanced digital technologies with genuinely human-centric approaches, the comprehensive assessment of social sustainability remains a critical challenge that limits organizations' ability to holistically manage their overall sustainability performance.

The article explores the transformative potential of Social Life Cycle Assessment within the United Nations Environment Programme stakeholder framework. The proposed methodology is simultaneously standardized, to ensure comparability and replicability, and data-driven, to minimize the subjectivity and arbitrary judgments that have characterized many previous approaches. The strategic integration of advanced statistical techniques, particularly Principal Component Analysis to identify underlying dimensions and sigmoid normalization to handle heterogeneous indicators, represents a significant methodological innovation and raises the quantitative rigor of social assessment to a level comparable with those already achieved in environmental assessment.

Empirical validation through an in-depth case study in the Italian ceramic industry, using primary internal organizational data carefully aligned with the guidelines for Social Organizational Life Cycle Assessment (SO-LCA), demonstrates not only the technical feasibility of the methodology but also its practical relevance for organizations seeking to strengthen regulatory compliance in a context of rapidly expanding ESG requirements.

The article is published in Corporate Social Responsibility and Environmental Management, a leading international journal indexed in Journal Citation Reports (JCR), where it attains a Journal Impact Factor of 9.1 and ranks in the first quartile (Q1) in the categories Environmental Studies, Management, and Business. The journal is also indexed in Scopus, with an SJR of 2.294, is classified as Q1 across all its areas (Strategy and Management; Management, Monitoring, Policy and Law; Development), and has an H-index of 129, underscoring its high impact and visibility in the fields of corporate sustainability and management. In addition, it is listed in the CABS Academic Journal Guide (AJG 2024), in the field of Regional Studies, Planning and Environment, with a rating of 1, reinforcing its position as one of the main journals specializing in corporate social responsibility and environmental management.

Fernández-Miguel, A., García-Muiña, F.E., Settembre-Blundo, D., et al. (2025). Unlocking the Social Promise of Industry 5.0: Harnessing Data-Driven Social Life Cycle Assessment for Corporate Sustainability. *Corporate Social Responsibility and Environmental Management*. https://doi.org/10.1002/csr.70128

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RESEARCH ARTICLE OPEN ACCESS

Unlocking the Social Promise of Industry 5.0: Harnessing Data-Driven Social Life Cycle Assessment for Corporate Sustainability

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Keywords: corporate sustainability reporting directive (CSRD) | data-driven approach | ESG strategies | industry 5.0 | regulatory compliance | social life cycle assessment (S-LCA) | social sustainability

ABSTRACT

In the contemporary era of Industry 5.0, characterized by the integration of digital technologies and human-centered approaches, the assessment of social sustainability remains a critical challenge. Corporate responsibility and Environmental, Social, and Governance compliance are being reshaped by these developments. This paper aims to address the gap between industrial development and social impact by exploring the transformative potential of Social Life Cycle Assessment within the stakeholder framework established by the United Nations Environment Program. The proposed methodology is both standardized and data-driven, employing advanced techniques such as Principal Component Analysis and sigmoid normalization to minimize subjectivity and enhance comparability. It is validated through a case study in the Italian ceramic industry, utilizing internal organizational data aligned with Social Organizational Life Cycle Assessment guidelines. The findings highlight the urgent need for reliable, data-driven social impact assessments to support regulatory compliance, strengthen Environmental, Social, and Governance strategies, and foster long-term corporate sustainability. Furthermore, the results demonstrate how integrating Social Organizational Life Cycle Assessment into Industry 5.0 frameworks can improve stakeholder engagement, drive social innovation, and contribute to sustainable business practices.

1 | Introduction

European companies face several barriers to systematically assessing the social sustainability impacts of their operations (Blandino and Montagna 2025). These challenges are multifaceted and include issues related to data availability, resources, regulatory frameworks, and organizational culture. Fragmented and insufficient data, along with the absence of standardized and objective metrics and benchmarks, hinder accurate measurement and reporting of social impacts (Kakogiannis 2024). The intangible, sensitive, and often context-specific nature of social impacts complicates quantification, whereas legal diversity across European countries creates inconsistent conditions for adopting uniform sustainability practices.

Corporate Social Responsibility (CSR) remains largely voluntary in many areas, reducing the enforcement of systematic assessments; organizational resistance to integrating social sustainability further hampers progress. Moreover, unclear stakeholder expectations and limited demand for detailed reporting reduce the perceived need for objective assessments (Paridhi et al. 2024). These challenges are further compounded by fragmented regulatory frameworks, weak stakeholder pressure, and poor integration into corporate governance models, all of which hinder the consistent adoption of social sustainability practices across Europe.

However, despite the EU Corporate Sustainability Reporting Directive (CSRD) mandating the disclosure of social indicators, empirical evidence on its effectiveness in enhancing organizational practices remains limited (Hristov and Searcy 2024). Currently, social sustainability evaluations still rely heavily on subjective assessments due to the lack of formalized evaluation techniques (Walker et al. 2021). For example, social indicators are not fully integrated into corporate decision-making via business intelligence systems, making it difficult to align assessments with broader organizational goals. Moreover, real-time databases built on objective indicators are not yet available to support systematic social sustainability assessments.

In response to these limitations, researchers have increasingly explored how information technology—particularly data analytics and machine learning—can improve the accuracy and reproducibility of social impact assessments (Varriale et al. 2023). Furthermore, recent legislative changes, such as the CSRD (European Commission 2021), emphasize the growing importance of social sustainability in business reporting, requiring companies to disclose non-financial social indicators as part of their broader ESG commitments (Hristov and Searcy 2024).

Previous studies have focused on existing social sustainability assessment frameworks, such as Social Return on Investment (SROI) and Social Impact Assessment (SIA). The SROI framework attributes economic value to social benefits, but it faces major limitations due to the subjectivity of assumptions and the difficulty in monetizing intangible outcomes (Gutiérrez-Nieto et al. 2025). By contrast, the SIA framework provides a holistic and participatory method for evaluating social impacts; yet, it is often complex, poorly standardized, and resource intensive (Alomoto et al. 2022). These frameworks are primarily qualitative and subjective, lacking the reproducibility and standardization required for strategic decision-making (Walker et al. 2021). Even structured tools like Social Life Cycle Assessment (S-LCA) and its organizational variant (SO-LCA) have not yet fully adopted quantitative methods capable of reducing subjectivity and enhancing cross-firm comparability (Gutierrez-Lopez et al. 2023).

Earlier applications of S-LCA in the Life Cycle Assessment domain have largely remained qualitative, context-specific, and methodologically inconsistent, limiting their replicability across sectors and alignment with Industry 5.0 principles or CSRD compliance. For instance, Graham et al. (2024) used participatory methods in a Canadian beef supply chain, relying on interviews, Q-method surveys, and interpretive synthesis to assess social performance, but lacked scalable indicators and cross-sector comparability. van Dulmen et al. (2025) critically evaluated S-LCA frameworks, noting that current methods struggle to establish causal links between social impacts and value-chain behaviors, suffer from ambiguous functional units, redundant indicator sets, and qualitative bias. Moreover, a recent systematic review of S-LCA in the construction sector highlights the use of inconsistent indicators, variable system boundaries, and sector-specific assumptions, leading to methodological fragmentation and limited generalizability of results (Ayassamy and Pellerin 2023).

These studies have also generally failed to address the comprehensive integration of social sustainability into Industry 5.0 frameworks (Santiago et al. 2025); nor have they examined the implications of Corporate Social Responsibility Disclosure (CSRD) on social sustainability initiatives. They lack systematic approaches capable of addressing the unique challenges of Industry 5.0 and of supporting the development of objective, reproducible methods for social sustainability assessment. New quantitative approaches using advanced statistical techniques, such as machine learning algorithms, are needed to ensure objectivity and replicability in these assessments. Therefore, there is a pressing need for robust, standardized methodologies that align with the human-centric principles of Industry 5.0 (Ghobakhloo et al. 2023). This study addresses this gap by enhancing the SO-LCA methodology through the integration of machine learning and data normalization techniques, offering a novel framework that supports both regulatory compliance and human-centered industrial transitions. The need for a comprehensive framework is further reinforced by the growing imperative to regulate social sustainability in manufacturing environments (Papetti et al. 2020).

The aim of this research is to enhance the Social Organizational Life Cycle Assessment (SO-LCA) methodology by integrating a data-driven approach to reduce subjectivity in social sustainability assessments. This integration seeks to overcome the limitations of traditional frameworks and ensure a more transparent, standardized, and reproducible model for corporate sustainability management. By leveraging advanced techniques such as Principal Component Analysis (PCA) and sigmoid normalization, the study proposes a more systematic and objective framework for evaluating social performance. Accordingly, this research addresses the following questions:

RQ1. How can data-driven methodologies improve the objectivity and reproducibility of social sustainability assessments in Industry 5.0?

RQ2. How can the integration of SO-LCA into corporate decision-making frameworks enhance ESG compliance and social responsibility?

The implementation of tools such as Social Life Cycle Assessment (S-LCA) is emerging as a strategic approach in today's data-driven, regulation-intensive business landscape (Gutierrez-Lopez et al. 2023). S-LCA offers a structured framework for assessing social impacts across the life cycle of products, processes, and organizations, addressing key dimensions such as labor conditions, stakeholder relationships, and community engagement (Bouillass et al. 2021).

This study underscores the transformative potential of a data-driven SO-LCA in bridging the gap between social sustainability and Industry 5.0. It offers businesses an objective and scalable approach to assess social impacts, whereas aligning with Life Cycle Thinking (LCT) principles and broader sustainability goals (Mesa Alvarez and Ligthart 2021). A key contribution is the development of a novel methodology that incorporates machine learning algorithms to minimize subjectivity in SO-LCA assessments and enhance comparability across firms, in line with UNEP guidelines. By leveraging advanced data analytics, this research provides firms with transparent and reliable tools for measuring and managing social impacts, thereby fostering a more inclusive and accountable sustainability framework. Furthermore, the study offers valuable insights for both scholars and practitioners aiming to integrate human-centered approaches into sustainability strategies, whereas balancing economic, environmental, and social objectives.

The remaining sections of the paper are organized as follows. The Theoretical Background reviews existing approaches, such as SROI and SIA, and discusses their limitations in assessing social sustainability. The Methodology section presents the hybrid qualitative–quantitative framework, justifies the case study selection, and outlines how SO-LCA has been adapted to the Industry 5.0 context. The Data Analysis and Results section provides empirical findings on social impacts derived from the revised SO-LCA approach. Finally, the Interpretation and Discussion sections examine the theoretical and practical implications of the results considering Industry 5.0 and the EU CSRD, followed by Conclusions that summarize key contributions, acknowledge limitations, and propose future research directions.

2 | Theoretical Background

2.1 | Exploring Social Sustainability Frameworks

The integration of diverse perspectives and needs relies on the consideration of stakeholder views regarding sustainable development and social relations as fundamental components (Colasante et al. 2024). The overarching objective is to promote equitable well-being (D'Adamo et al. 2024). Literature has explored a wide range of models to assess social sustainability, encompassing qualitative, quantitative, and mixed-method approaches (Govindan et al. 2021). Among these, several prominent frameworks offer distinct methods for evaluating the social dimension of sustainability (Ikram et al. 2020). One notable quantitative approach is Social Return on Investment (SROI), which assigns economic value to the social outcomes generated by an organization's activities (Ariza-Montes et al. 2021). SROI provides stakeholders with a monetized metric to assess social impact by comparing the benefits created with the investment required. Its process typically involves: (1) identifying relevant stakeholders, (2) mapping outcomes, (3) evaluating the effects, and (4) calculating the total social value generated (Nikolakis and da Veiga 2023). In contrast, Social Impact Assessment (SIA) offers a comprehensive framework for evaluating the social effects of proposed projects, policies, or regulations (Corvo et al. 2021). SIA captures both positive and negative impacts across multiple dimensions—economic, cultural, and environmental—by applying a mix of qualitative and quantitative tools. Its main goal is to support decision-making by identifying potential risks and opportunities for affected communities (Stjernborg 2023).

2.2 | Life Cycle Approaches: S-LCA and SO-LCA

Methodologies that systematically assess the social impacts of goods, services, or organizations across their life cycle—or within internal processes—include Social Life Cycle Assessment (S-LCA) and Social Organizational Life Cycle Assessment (SO-LCA) (D'Eusanio et al. 2022a). S-LCA extends the traditional Life Cycle Assessment (LCA) framework beyond environmental aspects to incorporate social concerns such as working conditions, human rights, and community engagement. It offers a comprehensive view of social impacts across the product life cycle, using both qualitative and quantitative indicators (Tokede and Traverso 2020). SO-LCA, by contrast, focuses on organizational-level assessment, capturing social aspects related to employee well-being, diversity, and stakeholder involvement (D'Eusanio et al. 2022b). A defining feature of both methods is their capacity to support the integration of social sustainability into corporate decision-making, helping firms align operational practices with broader sustainability goals (Huertas-Valdivia et al. 2020).

2.3 | Challenges in Social Sustainability Assessment

Although S-LCA and SO-LCA offer valuable support, significant implementation challenges persist. First, the lack of standardization leads to inconsistent protocols and divergent results across assessments (Mulloth and Rumi 2022). Second, the inherent subjectivity in data collection and analysis compromises the reliability and objectivity of results (Zheng et al. 2020). Additionally, nonstandardized documentation and methodological heterogeneity undermine the replicability of findings (Kalvani et al. 2021). Comparability is also a major concern due to variability in frameworks, indicators, and metrics. Moreover, manual data collection and analysis hinder scalability and increase the risk of error and inefficiency (Czaja-Cieszyńska et al. 2021). To address these issues, integration of social assessment models into organizational decision-making is essential (Walker et al. 2021). Leveraging business intelligence (BI) systems can bridge the gap between strategy and operations, improving alignment with ESG goals and enhancing the precision of social impact measurement (Karthik et al. 2025). Effective strategies include standardization, automation, enhanced objectivity, repeatability, and full integration into digital decision-making systems. Overcoming these barriers will enable companies to embed social sustainability evaluations into core processes and drive meaningful, long-term transformation.

2.4 | The Role of Regulatory Frameworks

The EU Corporate Sustainability Reporting Directive (CSRD) marks a major shift in the regulatory landscape, introducing stricter reporting obligations and greater transparency in corporate sustainability practices within the European Union (EU) (Richter et al. 2023). It significantly redefines expectations around environmental, social, and governance (ESG) accountability, requiring companies to disclose comprehensive nonfinancial information, including social indicators, in their annual reports (Arvidsson and Dumay 2022). Importantly, the CSRD extends its scope beyond individual firms to include their entire supply networks, underscoring the need for robust mechanisms to assess and monitor social risks across the value chain (Kilian-Yasin and Correa 2021; Villiers 2022). From raw material suppliers to end users, this expansion reinforces the imperative to regulate social sustainability throughout all supply chain tiers. As a result, there is a growing demand for effective tools and methodologies to conduct systematic social assessments, enabling companies to identify, track, and mitigate risks related to social performance (Lafarre 2023). By aligning with the goals of the CSRD (Samagaio and Diogo 2022), companies can ensure compliance while generating positive social impact across their operations and supplier ecosystems. Given this evolving legal context, adopting robust, data-driven approaches to manage social sustainability is no longer optional; it is a strategic necessity.

In this context, the application of Life Cycle Thinking (LCT) technologies is becoming increasingly critical to assess and minimize social impacts across the supply chain (Mohammad Ebrahimi and Koh 2021). Social Life Cycle Assessment (S-LCA) (Luthin et al. 2023) and Social Organizational Life Cycle Assessment (SO-LCA) (García-Muiña et al. 2021) provide structured methods for integrating social analysis within broader frameworks such as Life Cycle Assessment (LCA) (Kokare et al. 2023) and Organizational Life Cycle Assessment (O-LCA) (Cucchi et al. 2023) used for environmental performance. Integrating S-LCA and SO-LCA with conventional LCA and O-LCA tools enables businesses to adopt a comprehensive sustainability evaluation approach that aligns with CSRD requirements. This unified framework facilitates the identification of synergies and trade-offs between social and environmental goals, promoting more informed and integrated decision-making (Fernhaber and Hawash 2023). As regulatory pressure and stakeholder expectations intensify, the adoption of LCA-based techniques—particularly S-LCA and SO-LCA—is emerging as a strategic enabler of responsible governance and sustainability leadership (Mancini et al. 2023).

2.5 | Integrating Industry 5.0 and SO-LCA

The shift from Industry 4.0 to Industry 5.0 marks a significant evolution in industrial paradigms—moving beyond automation and efficiency toward greater emphasis on social sustainability, human-centricity, and ethical governance (Golovianko et al. 2023). Although Industry 4.0 prioritized digital automation and connectivity, it often neglected social and environmental dimensions. In contrast, Industry 5.0 integrates advanced technologies with inclusive and sustainable practices, centering on the human role in production (FengTang and Leong 2024). This paradigm promotes collaboration between humans and machines to enhance human capabilities, fostering flexible industrial environments that emphasize trust, engagement, and teamwork. These characteristics are closely linked to Sustainable Human Resource Management (SHRM), a key enabler of social sustainability (Sołtysik et al. 2024). Industry 5.0 also incorporates ESG principles, aligning with global sustainability goals by advancing ethical governance and reducing ecological impacts through AI, IoT, and blockchain technologies (Chandre et al. 2024; Rehman and Umar 2025). In this context, Social Life Cycle Assessment (S-LCA) aligns naturally with Industry 5.0 values, offering a structured method for assessing and improving social performance (Panza et al. 2023). Its organizational extension, SO-LCA, leverages data analytics and big data to measure social parameters objectively and consistently across sectors (García-Muiña et al. 2022). This enables firms to embed ethical principles into operations, ensuring economic viability, environmental sustainability, and social equity. Moreover, the ethical deployment of technology—a cornerstone of Industry 5.0—reinforces alignment with societal values and privacy protections (Barata and Kayser 2023). Transitioning to Industry 5.0 requires a redefinition of industrial frameworks to accommodate these human-centered and sustainability-oriented practices (Zizic et al. 2022). SO-LCA contributes to this transition by delivering actionable insights on social performance, strengthening CSR in the digital era (Kumari and Singh 2023). In doing so, SO-LCA transcends the efficiency-centric limitations of Industry 4.0, paving the way for a more inclusive and responsible industrial ecosystem.

2.6 | Industry 5.0 and the Imperative of Social Responsibility

The convergence of advanced digital technologies and human-centered principles in Industry 5.0 represents a fundamental transformation in manufacturing paradigms—one that emphasizes human capital, social well-being, and ethical responsibility (Ivanov 2023). In this context, the obligations introduced by the EU CSRD reinforce the need for businesses to assess and manage the social impacts of their operations. Unlike previous industrial revolutions, which focused on productivity and efficiency, Industry 5.0 prioritizes inclusive growth, employee empowerment, and ethical practices across the value chain (Atif 2023). As a result, manufacturers are under increasing pressure to evaluate their labor practices, diversity, workplace well-being, and community engagement (Alojaiman 2023). Embedding social responsibility into business strategies has been shown to strengthen brand reputation, stakeholder trust, innovation capacity, and long-term value creation (Torres de Oliveira et al. 2023). In parallel, CSRD regulations require a systematic and transparent approach to assessing and communicating social performance (Ortiz-Martínez et al. 2023). The alignment between Industry 5.0 and CSRD highlights the growing awareness of the interdependence between corporate activity and societal well-being. This convergence calls on companies to treat social responsibility not as a secondary concern, but as a strategic pillar of industrial transformation (Asif et al. 2023).

3 | Methodology

This research proposes a mixed-method approach, revising the SO-LCA methodology to enhance objectivity in social sustainability assessments within the manufacturing sector. By integrating Industry 5.0 principles and advanced data-driven models, the new methodology aims to reduce the subjectivity typically found in traditional SO-LCA methods, which often rely on qualitative data. The proposed methodology is structured in accordance with the ISO 14044 framework, traditionally applied in environmental assessments. This framework includes goal and scope definition, inventory analysis, impact assessment, and interpretation. Although aligned with UNEP guidelines, the revised approach introduces quantitative processes to improve comparability across companies. This structured design clarifies the social sustainability assessment and supports its application in various industrial contexts.

To ensure consistency and comparability, the methodology applies two advanced quantitative techniques: Sigmoid Normalization and Principal Component Analysis (PCA). Sigmoid normalization was selected for its ability to scale data within a bounded range (0–1) while maintaining the proportional relationships between values. Unlike min–max scaling, which can be heavily influenced by outliers, sigmoid normalization minimizes such effects, producing balanced transformations across indicators. For example, workplace safety data (e.g., incident rates) and community engagement metrics (e.g., number of initiatives) were normalized using the sigmoid function, ensuring cross-indicator consistency despite differences in scale or units. PCA was chosen to address dimensionality reduction while preserving the most relevant information in the dataset. By grouping correlated variables into principal components, PCA reduces redundancy and reveals underlying patterns. In contrast to manual weighting or expert judgment, PCA provides an objective, data-driven weighting mechanism, enhancing reproducibility and transparency.

During the data collection phase, indicators such as safety records, stakeholder engagement, and supplier performance were collected from multiple sources, including employee surveys and supplier audits. These raw data points were first normalized using the sigmoid function to ensure comparability. Then, PCA was applied to aggregate them into composite indices, such as Worker Well-being and Community Development. This approach streamlined the evaluation process and delivered actionable insights by identifying priority areas for improvement. The efficacy of the revised methodology was tested through a case study of a leading Italian ceramic tile manufacturer, known for its Industry 5.0 initiatives and its experience with environmental assessments through ERP systems. This company served as an ideal test case to validate the new approach. The case study demonstrated the methodology's potential to bridge the gap between social and environmental sustainability evaluations, offering a more integrated and objective assessment.

Given the current lack of primary social data, this research initially combines the quantitative model with expert committee input based on prior studies (García-Muiña et al. 2021). However, as more companies adopt this framework and contribute data, the long-term goal is to develop a fully quantitative, standardized model for social sustainability assessment—thereby reducing reliance on subjective inputs.

4 | Results

This section provides a step-by-step guide to implementing the revised SO-LCA methodology, particularly in the context of the manufacturing sector. The structure follows the four standard phases of the ISO 14044 framework: Goal and Scope Definition, Inventory Analysis, Impact Assessment, and Interpretation. The proposed approach introduces innovative techniques while remaining aligned with UNEP guidelines, offering a more detailed and accurate representation of social sustainability performance.

4.1 | Goal and Scope Definition

The methodology was applied across three production facilities and the headquarters of a ceramic tile manufacturing company. The adoption of digital technologies in manufacturing and business operations enabled the collection of primary social data in real time. In line with UNEP's SO-LCA framework, the reporting organization was defined using a "cradle-to-grave" system boundary, serving as the unit of analysis.

Stakeholder identification and classification followed UNEP's six stakeholder categories and four impact categories, with flexibility to adjust based on specific value chain needs. In this study, the stakeholder groups included: workers, local communities, society, consumers, and value chain actors. The children category was excluded, as it was not relevant to the company's supply chain. Stakeholders were selected based on their relevance within the firm's operational value chain, enabling the evaluation of effects through primary data-driven social metrics. The impact categories adopted align with sustainable capital theory, encompassing human, social, natural, and economic capital. Subcategories were generated in accordance with the UNEP SO-LCA methodological guidelines. In particular, the "Environment" subcategory under the Society stakeholder group allowed for a direct link to parallel environmental assessments. Table 3 presents the Industry 5.0–based stakeholder classification and corresponding effect categories used in the study.

4.2 | Inventory Analysis

The use of digital technologies to automatically aggregate data from both headquarters and production sites enables the implementation of an Industry 5.0–based inventory analysis within the SO-LCA program. The ERP system functions as the technical hub, collecting real-time production and management data, which is then connected to a Business Intelligence (BI) platform interfacing with the SO-LCA calculation tool (Figure 1). This integration between digital and physical systems facilitates real-time monitoring of social impacts. Although the model is especially suitable for digitally mature firms, it can also be adapted for organizations still relying on conventional analog data collection, thus supporting gradual digitalization. The combination of ERP, BI, and Industry 5.0 technologies enables cloud-based dynamic inventory analysis (DIA), allowing for continuous, real-time social performance evaluation.

The DIA process begins with the identification of measurable social indicators that are contextually relevant and feasible for primary data collection. A technical-scientific committee selected these indicators by developing a correlation matrix that links stakeholder categories to their corresponding impact domains. For instance, indicators such as collective bargaining agreements

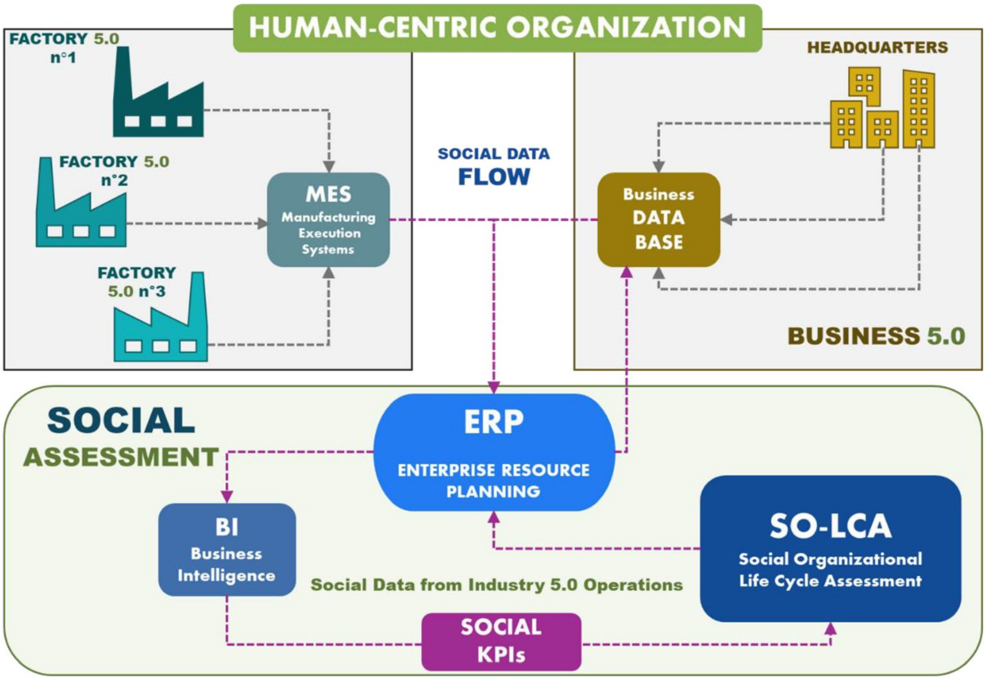

FIGURE 1 | Data-driven social organizational life cycle assessment, adapted from García-Muiña et al. (2022).

(CBAs) and the provision of personal protective equipment (PPE) are associated with workers and relate to human capital impacts. Likewise, interactions with local governments and community stakeholders serve as metrics for local communities within the domain of social capital, whereas measures like research and innovation hours and regulatory participation are used to capture broader societal impacts aligned with natural and social capital. Additionally, revenue generated and non-compliance costs are included to reflect the perspective of consumers and value chain actors. Altogether, the inventory analysis incorporates 46 company-specific social indicators, which are aggregated into 28 Dynamic Social Indicators (DSIs). These DSIs enable a clear classification of the organization's social impacts as either positive or negative, as presented in Table 1.

4.3 | Context-Aware Social Impact Assessment

The impact assessment method establishes a hierarchical structure that links individual social indicators to two levels of evaluation: impact subcategory indices (midpoints) and impact category indices (endpoints). This framework allows for a comprehensive measurement of how the organization's operations affect various stakeholder groups. The analysis is based on 46 social indicators, systematically organized into 28 Dynamic Social Indicators (DSIs). These indicators, collected between 2021 and 2023 (see Table 4), form the foundation of a structured and replicable assessment framework. Each indicator is evaluated in terms of whether increases or decreases in its value represent a positive or negative social effect, enabling a clear and actionable interpretation of results.

In line with dynamic Life Cycle Assessment (LCA) principles, this phase of the analysis focuses on processing the DSI ratios to determine their contributions to midpoint and endpoint scores for each impact subcategory and category. Data is scaled and quantified objectively, with each indicator weighted according to its relative importance within its corresponding impact dimension. These results are then integrated into a consolidated Dynamic Sustainability Index, offering a comprehensive and robust metric for evaluating overall social sustainability performance. The final index highlights key strengths and opportunities for improvement, supporting strategic decision-making and stakeholder communication.

Accurate interpretation and comparison of multiple indicators require scaling procedures that maintain the intrinsic structure of the data. Two commonly used approaches are data normalization (adjusting values to a mean of zero and standard deviation of one) and min–max standardization (scaling values to a 0–1 range). Although normalization supports direct comparison, it can complicate aggregation due to value heterogeneity (Gee et al. 1997). In contrast, min–max standardization simplifies interpretation but is vulnerable to outliers, potentially leading to misleading conclusions, especially in small datasets. To address these limitations, the methodology adopts a hybrid transformation: normalization followed by sigmoid scaling, a logarithmic function that bounds values between 0 and 1. This method preserves significant variation in the original data while reducing the influence of extreme values, making it particularly suitable for social sustainability studies, where datasets may be limited and indicator variability high. This integrated approach combines the strengths of both normalization and standardization, offering a balanced and robust solution for ensuring accurate and meaningful indicator comparisons (Allen et al. 2021). The mathematical transformation used in this method is presented below:

$$\sigma\left(\frac{x-\mu}{\sigma}\right) = \frac{1}{1+e^{\left(\frac{x-\mu}{\sigma}\right)}}$$

TABLE 1 | Dynamic inventory analysis data base.

Stakeholder categories	Impact categories	Stakeholder subcategories	Impact subcategories	Dynamic social indicators		Indicators description by metrics	Social positive influence
1. Workers	A. Human capital	1.1 Staff personnel	A1. Human rights	DSI-A1.1	Gender equality	(No. of women)/(total workforce)	INCREASE
				DSI-A1.2	Childhood workforce	(No. of children)/(total workforce)	DECREASE
				DSI-A1.3	Forced labour	(No. of forced labor workers)/(total workforce)	DECREASE
				DSI-A1.4	Migrant worker	(No. of migrant workers)/(total workforce)	INCREASE
			A2. Health and safety	DSI-A2.1	Lost time injury frequency rate (LTIFR)	(NO. of injuries x 1,000,000) / (Hours worked)	DECREASE
				DSI-A2.2	Personal protective equipment (PPEs)	(No. of PPEs)/(total workforce)	INCREASE
		1.2 Trade unions	A3. Working conditions	DSI-A3.1	Collective bargaining agreement (CBA)	(No. CBA)/(total workforce)	INCREASE
				DSI-A3.2	Overtime working hours	(Man-hours overtime)/(hours worked)	DECREASE
				DSI-A3.3	Full-time staff	(Full-time staff)/(total workforce)	INCREASE
				DSI-A3.4	Local workforce	(Local workforce)/(total workforce)	INCREASE
				DSI-A3.5	Training	(Training hours)/(hours worked)	INCREASE
2. Local community	B. Social capital	2.1 Local institutions	B1. Local expectations	DSI-B1.1	Stakeholders engagement	(Stakeholders engaged/stakeholders mapped)	INCREASE
				DSI-B1.2	Public engagement	(Local governments engaged/No. local governments)	INCREASE
3. Society		3.1 Public and private organizations	B2. Institutional expectations	DSI-B2.1	University engagement	(Man-hours of scientists)/(Man-hours into R&D&I)	INCREASE
				DSI-B2.2	Regulatory authorities engagement	(Authorities engaged)/(No. of regulatory authorities)	INCREASE

(Continues)

TABLE 1 | (Continued)

Stakeholder categories	Impact categories	Stakeholder subcategories	Impact subcategories	Dynamic social indicators		Indicators description by metrics	Social positive influence
		3.2 Media	B3. Corporate reputation	DSI-B3.1	Corporate social media engagement	(Corporate followers/ corporate likes)	INCREASE
				DSI-B3.2	B2B social media engagement	(B2B followers/B2B likes)	INCREASE
				DSI-B3.3	B2C social media engagement	(B2C followers/B2C likes)	INCREASE
	C. Natural capital	3.3 Environmental	C1. Carbon footprint	DSI-C1.1	Global warming potential (GWP)	(Company GWP/industry GWP)	DECREASE
4. Consumers	D. Economic capital	4.1 Trade channel operators	D1. Customer expectations	DSI-D1.1	B2B non-compliance	(B2B non-compliance costs)/(B2B turnover)	DECREASE
		4.2 Final consumer		DSI-D1.2	B2C non-compliance	(B2C non-compliance costs)/(B2C turnover)	DECREASE
5. Value chain actors		5.1 Private business	D2. Private expectations	DSI-D2.1	HR-based R&D workforce	(Researchers staff)/ (total workforce)	INCREASE
				DSI-D2.2	HR-based innovation workforce	(Innovators staff)/ (total workforce)	INCREASE
				DSI-D2.3	R&D & innovation	(R&D&I. invest.)/(total invest.)	INCREASE
		5.2 Suppliers	D3. Ethical behavior	DSI-D3.1	Order approval manager	(No. of approved orders/ No. of total orders)	INCREASE
				DSI-D3.2	Ethical key suppliers	(Ethical key suppliers/ total key suppliers)	INCREASE
				DSI-D3.3	Local suppliers	(Local suppliers/total suppliers)	INCREASE
				DSI-D3.4	Local suppliers turnover	(Local suppliers turnover/ key suppliers turnover)	INCREASE

where x is the input value to be standardized and transformed. μ is the mean of the dataset, which helps center the data around 0. σ is the standard deviation of the dataset, which scales the data so that it has a unit variance. $\left(\frac{x-\mu}{\sigma}\right)$ represents the sigmoid function applied to the standardized value of x.

The weighting of indicators enables their aggregation into corresponding Dynamic Social Indices (DSIs), ultimately allowing the calculation of a composite dynamic sustainability index. To facilitate this, dimensionality reduction techniques are employed to consolidate original indicators into impact indexes that better reflect their underlying behavior. Within the Life Cycle Thinking framework, common weighting approaches include equal weighting, expert judgment, and the Analytic Hierarchy Process (AHP) (Alyami et al. 2015). However, these methods are inherently subjective, often shaped by personal preferences or contextual biases.

To overcome this limitation, the methodology employs Principal Component Analysis (PCA)—a robust statistical technique that reduces dimensionality while retaining the most informative variation in the data. PCA provides an objective, analytical basis for weighing and aggregating indicators. By applying PCA to each effect category and extracting the first principal component (PC1), the model derives a polynomial that reflects the relative variability contributed by each indicator (Mohsine et al. 2023). PC1 is computed as a linear combination of the original indicators, where each variable is multiplied by a coefficient corresponding to its informative weight. These PC1 scores serve as the composite index for each social impact category and are used to weigh and aggregate indicators in a scientifically grounded manner. This approach ensures maximum information retention while minimizing subjective bias in index construction.

The analytical workflow was implemented using R programming language, through a custom-built script specifically designed to meet the requirements of this study. The process began by dividing the dataset according to impact categories. Then, aggregate weights for each indicator were computed using the prcomp() function (Settanni 2024) to extract the PC1 coefficient vector. An ad hoc function was used to rescale the coefficients, ensuring that all weights were positive and summed to one. The next step involved scaling the database using a sigmoid transformation, preceded by normalization to standardize the indicator values. A custom function applied the sigmoid scaling to each indicator. Finally, the scaled data was multiplied by the weight vectors, resulting in a complete matrix representing each social effect index. This procedure was then repeated using PCA on the full matrix of effect category indexes, enabling the computation of the global social sustainability index. A detailed mathematical representation of this PCA-based process is provided in Table 2.

4.4 | Interpretation of Assessment Results

This section presents the results of the Social Organizational Life Cycle Assessment (SO-LCA) and focuses on two main components. First, it analyzes the weighting and aggregation of Dynamic Social Indicators (DSIs) using a mixed-method

TABLE 2 | Principal component analysis process applied to sustainable index definition.

Step 1: Calculating the first principal component (PC1)

Given a set of social indicators $X = [x_1, x_2, \ \ldots \ , x_n]$ where each x_i represents an indicator and n is the total number of indicators, PCA transforms this set into principal components.
The first principal component (PC1) is calculated by finding the vector of coefficients $a = [a_1, a_2, \ \ldots \ , a_n]$ that maximizes the variance of X projected onto a subject to $\|a\| = 1$. This can be formulated as the optimization problem:
$\max_a Var(Xa)$ subject to $\|a\|^2 = 1$

Step 2: Representation of PC1

PC1 is represented as the weighted sum of the original indicators by their coefficients:
$PC1 = a_1x_1 + a_2x_2 + \ \ldots \ + a_nx_n$
This can be expressed in matrix form as $PC1 = Xa$.

Step 3: Weighting the coefficients

To ensure the coefficients are positive and sum to one, we perform a normalization:
$a_i' = \frac{|a_i|}{\sum_{k=1}^{n} |a_k|}$
This transforms each a_i coefficient into a weight a_i' for the corresponding indicator, ensuring all weights are positive and their sum equals 1.

Step 4: Calculating the social impact index

Finally, the value of the social impact index for a category j is calculated by multiplying each indicator by its weighted coefficient and summing the results:
$$\text{Index}_j = \sum_{i=1}^{n} a_i' x_i$$
This provides an aggregated value or Index that represents the impact of category j that retains most of the original variability, considered as the information provided by each indicator.

TABLE 3 | Weighting criteria of dynamic social indicators DSI and impact subcategories.

Dynamic social indicators	Indicator weight			Impact subcategories	Index weight			Impact categories
	Experts	PCA	Mixed		Experts	PCA	Mixed	
Gender equality	20%	50.0%	35.0%	Human rights	30%	41.4%	35.7%	Human capital
Childhood workforce	35%	0.0%	17.5%					
Forced labour	35%	0.0%	17.5%					
Migrant worker	10%	50.0%	30.0%					
Lost time injury frequency rate (LTIFR)	80%	50.0%	65.0%	Health and safety	30%	46.8%	38.4%	
Personal protective equipment (PPEs)	20%	50.0%	35.0%					
Collective bargaining agreement (CBA)	30%	0.0%	15.0%	Working conditions	40%	11.8%	25.9%	
Overtime working hours	10%	25.5%	17.7%					
Full-time staff	20%	24.2%	22.1%					
Local workforce	20%	25.1%	22.6%					
Training	20%	25.1%	22.6%					
Stakeholders engagement	60%	100.0%	80.0%	Local expectations	30%	26.4%	28.2%	Social capital
Public engagement	40%	0.0%	20.0%					
University engagement	60%	50.0%	55.0%	Institutional expectations	20%	35.5%	27.7%	
Regulatory authorities engagement	40%	50.0%	45.0%					
Corporate social media engagement	25%	39.8%	32.4%	Corporate reputation	50%	38.2%	44.1%	
B2B social media engagement	30%	24.9%	27.4%					
B2C social media engagement	45%	35.3%	40.1%					
Global warming potential (GWP)	100%	100.0%	100.0%	Carbon footprint	100%	100%	100%	Natural capital
B2B non-compliance	50%	50.0%	50.0%	Customer expectations	40%	42.1%	41.1%	Economic capital
B2C non-compliance	50%	50.0%	50.0%					
HR-based R&D workforce	20%	33.5%	26.7%	Private expectations	30%	32.7%	31.3%	
HR-based innovation workforce	20%	33.3%	26.6%					
R&D & innovation	60%	33.2%	46.6%					
order approval manager	30%	34.1%	32.0%	Ethical behavior	30%	25.2%	27.6%	
Ethical key suppliers	20%	32.1%	26.0%					
Local suppliers	25%	1.2%	13.1%					
Local suppliers turnover	25%	32.7%	28.9%					

approach that combines expert consultation with Principal Component Analysis (PCA). This integrated methodology supports a more balanced and objective evaluation of social performance by reconciling expert knowledge with data-driven insights. The section also discusses the challenges posed by limited data availability and variability in certain indicators, which can affect result interpretation.

Table 3 presents the weighting values assigned to each DSI and its corresponding impact subcategory. Final weights result from the combined application of qualitative expert judgment and PCA-derived quantitative scores. Although general alignment between expert input and PCA outcomes was observed, some adjustments were necessary. For example, expert consultation emphasized the relevance of indicators related to child labor

TABLE 4 | Social organizational assessment indexes values.

Dynamic social indicators	2021	2022	2023	Impact subcategories	2021	2022	2023	Impact categories	2021	2022	2023
Gender equality	0.499	0.501	0.500	Human rights	0.4998	0.5004	0.4998	Human capital	0.503	0.498	0.499
Childhood workforce	0.500	0.500	0.500								
Forced labour	0.500	0.500	0.500								
Migrant worker	0.500	0.500	0.500								
Lost time injury frequency rate (LTIFR)	0.513	0.491	0.496	Health and safety	0.5083	0.4944	0.4973				
Personal protective equipment (PPEs)	0.499	0.500	0.500								
Collective bargaining agreement (CBA)	0.500	0.500	0.500	Working conditions	0.4997	0.4998	0.5005				
Overtime working hours	0.500	0.500	0.500								
Full-time staff	0.499	0.499	0.502								
Local workforce	0.499	0.500	0.501								
Training	0.500	0.500	0.500								
Stakeholders engagement	0.497	0.503	0.500	Local expectations	0.4978	0.5021	0.5001	Social capital	0.443	0.499	0.558
Public engagement	0.500	0.500	0.500								
University engagement	0.467	0.467	0.565	Institutional expectations	0.4521	0.4857	0.5621				
Regulatory authorities engagement	0.434	0.508	0.558								
Corporate social media engagement	0.330	0.580	0.595	Corporate reputation	0.4019	0.5053	0.5916				
B2B social media engagement	0.388	0.388	0.713								
B2C social media engagement	0.469	0.526	0.505								
Global warming potential (GWP)	0.503	0.496	0.501	Carbon footprint	0.5030	0.4959	0.5011	Natural capital	0.503	0.496	0.501
B2B non-compliance	0.500	0.500	0.500	Customer expectations	0.5000	0.4999	0.5001	Economic capital	0.498	0.501	0.501
B2C non-compliance	0.500	0.500	0.500								
HR-based R&D Workforce	0.500	0.500	0.500	Private expectations	0.4958	0.5002	0.5040				
HR-based innovation workforce	0.499	0.500	0.501								
R&D & innovation	0.491	0.501	0.508								
Order approval manager	0.503	0.498	0.499	Ethical behavior	0.4980	0.5041	0.4979				
Ethical key suppliers	0.480	0.522	0.498								
Local suppliers	0.500	0.501	0.499								
Local suppliers turnover	0.508	0.496	0.496								

and migrant workers, but PCA assigned them lower weights due to the limited variability in the data. Some impact areas, such as Stakeholder Engagement and Public Engagement for Local Expectations, exhibited homogeneous results, reflecting low variation across the dataset. Nevertheless, the fusion of both methods created a more balanced and defensible aggregation strategy, mitigating the weaknesses inherent in either approach used independentl.

Table 4 presents the social indicator values at the organizational level, along with their aggregation across 10 subcategories and four final impact categories. Interestingly, many indicators values cluster around 0.5, which can be explained by three factors: (1) the company-specific reference values used for benchmarking; (2) the sigmoid normalization function, which typically centers values around 0.5; and (3) the consistency of indicator performance over the three-year data collection period. As more organizations contribute to this dataset, the model's comparative robustness and benchmarking potential will increase, enhancing the generalizability of the findings.

The findings confirm that integrating expert opinion and PCA enables a more nuanced and methodologically rigorous SO-LCA evaluation. Although expert judgment highlights strategic issues, PCA reinforces objectivity and transparency by basing weightings on statistical variability. Despite current limitations in dataset size and indicator volatility, the combined approach improves the reliability of social impact assessments. As the model evolves with additional data contributions, its capacity to generate accurate, actionable, and replicable results will strengthen, offering practical value for organizational decision-making.

This revised methodology also leads to the development of a conceptual model (Figure 2) that links the European Corporate Sustainability Reporting Directive (CSRD), the principles of Industry 5.0, and the strategic role of SO-LCA in promoting social sustainability within manufacturing ecosystem.

Figure 2 illustrates how the CSRD, as a regulatory framework, serves as the foundation for advancing social sustainability under the Industry 5.0 paradigm. It mandates rigorous reporting on social dimensions, such as decent work conditions and human rights, whereas encouraging standardized metrics for cross-industry comparability. In contrast, Industry 4.0, with its emphasis on efficiency and automation, often lacks mechanisms to address social impacts, resulting in missed opportunities to mitigate systemic inequalities across global value chains. In response, Industry 5.0 emerges as a paradigm shift that centers on human well-being, ethical responsibility, and the productive use of digital technologies for societal benefit. It explicitly integrates social objectives into manufacturing design, empowering firms to align technological innovation with human-centered values. By emphasizing worker welfare, expanded stakeholder engagement, and data-driven governance, Industry 5.0 paves the way toward a more inclusive and resilient production system.

The model highlights how SO-LCA bridges the gap between these two dimensions. It provides a structured, data-driven means to evaluate social performance, satisfy CSRD obligations, and embed Industry 5.0 criteria into corporate sustainability strategies. SO-LCA thus functions as both a diagnostic tool and a regulatory compliance mechanism, supporting companies in translating abstract policy mandates into concrete, measurable practices.

Overall, the integration of SO-LCA, Industry 5.0, and CSRD—as captured in the conceptual model—offers a strategic roadmap for manufacturers seeking to move beyond the limitations of Industry 4.0 and embrace a new paradigm of sustainable, equitable, and ethically grounded industrial development.

5 | Discussion

The findings of this study demonstrate that subjectivity in social sustainability evaluations can be significantly reduced through the application of data-driven methodologies, as implemented in the revised SO-LCA model. Traditional approaches, such as Social Return on Investment (SROI) or Social Impact Assessment (SIA), often rely heavily on qualitative data and expert judgment, leading to variability and limited comparability across contexts. In contrast, the SO-LCA model introduces quantitative techniques, including Principal Component Analysis (PCA) and sigmoid normalization, to standardize and analyze social indicators more objectively and reproducibly.

This methodological shift addresses the longstanding challenge of inconsistency in conventional models by promoting replicability and cross-context comparability. Furthermore, the integration of machine learning elements and normalization algorithms enhances the model's ability to minimize bias, offering a more accurate, transparent, and reliable assessment of social impacts. These findings support the argument that quantitative methods are essential to improving the credibility and scientific rigor of social sustainability assessments in Industry 5.0 environments.

The Industry 5.0 paradigm, with its emphasis on human-centric innovation and technological integration, offers a compelling framework for advancing transparency and accountability in social sustainability. The SO-LCA model is fully aligned with this paradigm, leveraging real-time monitoring capabilities and data integration to ensure comprehensive evaluations of social performance. Technologies such as the Internet of Things (IoT) and blockchain can be integrated into the model to enhance traceability across the supply chain, enabling organizations to measure and report social impacts consistently and reliably.

These technological advancements directly address the shortcomings of earlier methodologies, providing stakeholders with actionable insights based on real-time, verifiable data. Moreover, the model's compatibility with evolving regulatory frameworks, such as the EU Corporate Sustainability Reporting Directive (CSRD), positions it as a valuable tool for both legal compliance and stakeholder trust-building. By demonstrating accountability, companies can strengthen their ESG credentials and align more effectively with societal expectations. The integration of Industry 5.0 technologies and the SO-LCA model thus bridges critical gaps in transparency and facilitates more effective ESG strategies.

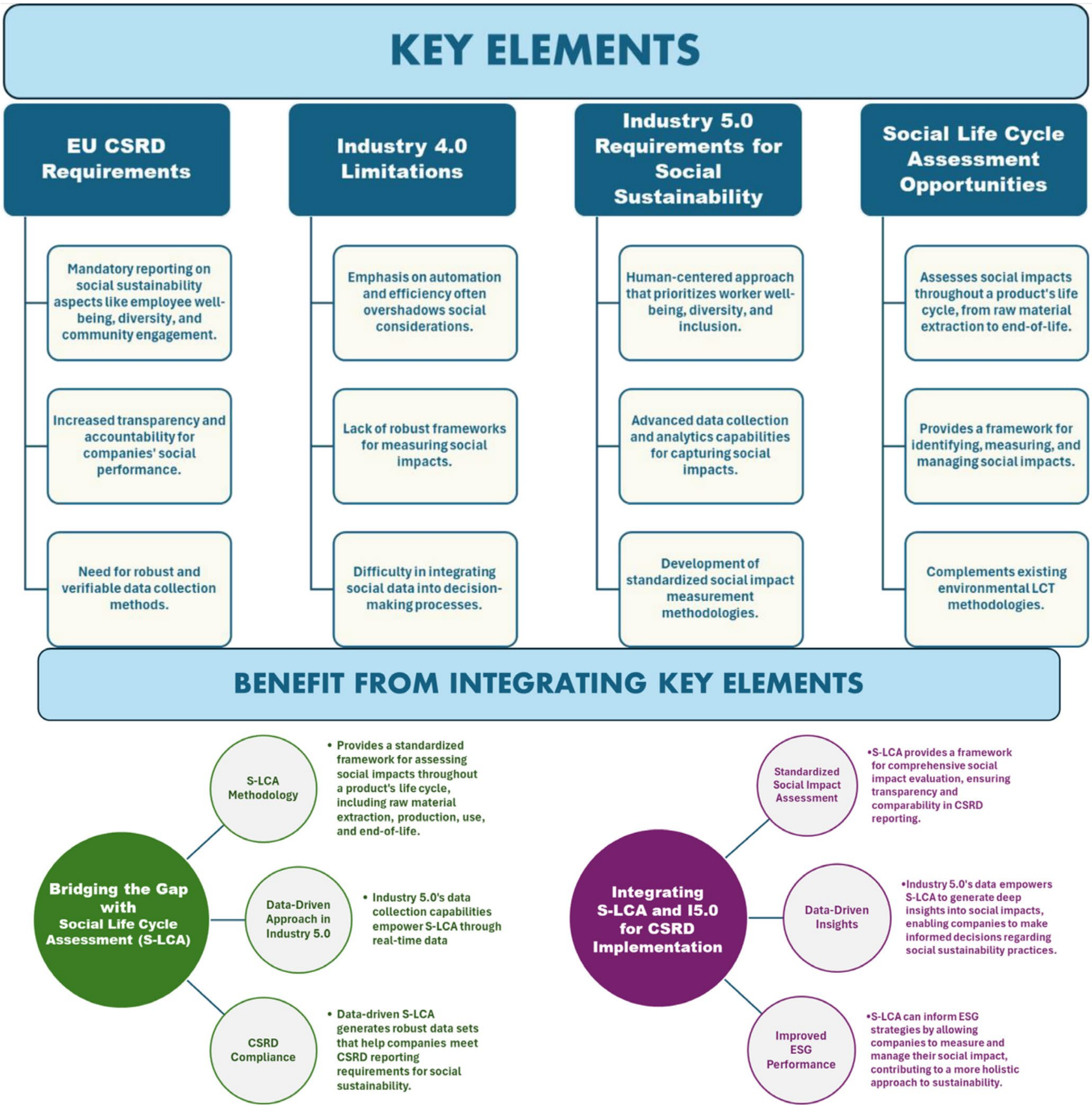

FIGURE 2 | Conceptual framework for implementing the EU CSRD in industry 5.0 with a focus on social sustainability.

A comparative analysis between the SO-LCA model and more traditional methodologies, such as SROI, highlights the limitations of relying predominantly on subjective evaluations and static reporting tools. Although SROI can yield insights into social value creation, its qualitative foundation often results in inconsistent applications and outcomes. The SO-LCA model addresses these limitations by incorporating advanced analytics and standardized procedures, enabling scalability, replicability, and data-driven decision-making.

Additionally, existing literature has emphasized the difficulty of reconciling detailed social reporting with accessibility for stakeholders. The SO-LCA model mitigates this by offering dynamic dashboards that transform complex data into intuitive visualizations, enhancing usability without sacrificing analytical depth. These innovations not only increase the practical applicability of the model but also respond to the demands of Industry 5.0, where transparency, real-time feedback, and technological integration are central to sustainable business practice.

6 | Conclusions

The findings of this research emphasize the strategic importance of integrating a mixed-method approach into the current SO-LCA model by combining expert consultation with PCA and Sigmoid Normalization techniques. Compared to conventional methods, this integration enhances the model's ability to offer a more comprehensive and objective evaluation of social indicators, improving both transparency and accountability. By merging qualitative insights with advanced quantitative techniques, this methodology strengthens the accuracy, reliability, and replicability of assessments. It also delivers a more granular understanding of social impacts, which is essential for informed decision-making in a complex, data-driven market. Specifically, in the context of Industry 5.0, the study highlights the transformative potential of a data-driven Social Organizational Life Cycle Assessment (SO-LCA) in fostering social sustainability. The integration of SO-LCA into organizational decision-making frameworks reinforces ESG compliance, supports transparency, and enables a systematic approach to social responsibility. In this respect, SO-LCA allows companies to identify areas requiring social transformation, strengthen their ESG performance, and align operational strategies with long-term sustainability goals. This integration also enhances corporate positioning in the ESG investment landscape by demonstrating measurable commitment to social performance.

From a theoretical standpoint, this study contributes to the literature on social sustainability assessment by advancing the SO-LCA methodology in three key ways. First, it addresses a significant gap by incorporating quantitative methods, such as PCA and sigmoid normalization, into a framework traditionally dominated by qualitative and subjective assessments. In doing so, the research supports calls for greater methodological rigor (Díaz-Reza et al. 2024; Singh and Cohen 2025) and offers a replicable and standardized approach to improve comparability across organizations. Second, the study contextualizes SO-LCA within the evolving Industry 5.0 paradigm, providing theoretical insight into how human-centric, digitally enabled manufacturing systems can operationalize social responsibility. Third, the proposed framework builds a conceptual bridge between Industry 5.0 principles and the European CSRD regulatory mandates, promoting not only regulatory compliance but also a shift toward more responsible and adaptive business practices.

From a managerial perspective, the study offers actionable guidance for companies aiming to align their operations with economic, social, and environmental sustainability objectives. It demonstrates how Business Intelligence (BI) platforms can incorporate objective social sustainability criteria through the application of data-driven SO-LCA. This allows organizations to integrate social data into strategic decision-making, facilitate organizational change, and strengthen overall sustainability performance. The integration of SO-LCA into existing Enterprise Resource Planning (ERP) systems further enables real-time social performance monitoring, supporting evidence-based decisions and improving ESG alignment. Moreover, by leveraging the vast volume of social data generated by Industry 5.0 operations (e.g., safety records, employee surveys, and supplier audits), companies can conduct in-depth analyses of value chain impacts. For example, by using supplier-related indicators—such as ethical compliance, local sourcing, or workforce innovation—firms can enhance supply chain responsibility and transparency. The SO-LCA model also facilitates CSRD compliance through the adoption of normalized and weighted indicators and transparent aggregation methods, resulting in audit-ready social sustainability reports that strengthen both regulatory alignment and stakeholder trust. In this way, the proposed data-driven SO-LCA framework offers an effective tool for improving ESG strategy execution by identifying priority areas, ensuring operational alignment with social responsibility goals, and providing granular insights into supply chain performance.

Despite its contributions, this study has several limitations that open avenues for future research. First, the focus on a single case study within the ceramic industry restricts generalizability. Sector-specific social dynamics may differ in healthcare, energy, or services, and future research should test this methodology across other industries. Second, reliance on a single firm limits external validity. Multiple case studies would enhance the robustness and transferability of findings. Third, while the study integrates expert judgment to address data limitations, it still introduces a degree of subjectivity. Future research could involve systematic primary data collection using real-time technologies such as IoT monitoring and digital supply chain analytics, alongside the development of an open-access social indicator database for benchmarking. Fourth, since the methodology has been applied to a large firm, future studies should explore its adaptability to SMEs, assessing scalability, cost-effectiveness, and operational feasibility in small-scale contexts. Additionally, research should investigate the development of a common unit of measurement to integrate social impact metrics with environmental, economic, and technological indicators under the broader Life Cycle Thinking framework. Future studies may also examine how emerging technologies such as blockchain and AI can improve traceability, data reliability, and transparency in social reporting. Another promising direction would be a comparative analysis of how companies are implementing the CSRD to identify best practices, challenges, and regulatory implications for advancing social sustainability.

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PART III – SYNTHESIS, CONCLUSIONS, AND FUTURE DIRECTIONS

5 SYNTHESIS AND INTEGRATION OF RESULTS

This section synthesizes and integrates the results of the three articles that make up the compendium, explicitly situating them within the research program defined in Part I. First, it shows how each publication contributes to the specific objectives of the dissertation, addressing in a complementary way the territorial-contextual, physical-thermodynamic, and data-driven social dimensions of systemic sustainability. It then analyzes the conceptual and methodological connections among the three blocks, as well as the role of the Italian ceramic district and the Industry 5.0/6.0 paradigm as guiding threads. Taken together, the section shows how these partial contributions combine to form an integrated vision of systemic sustainability that is compatible with agile strategies in complex manufacturing supply chains.

5.1 Research program and coherence of the compendium

5.1.1 First article: geoanthropological approach and systemic sustainability index

The first article responds primarily to the objective of exploring the applicability of the geoanthropological approach as a strategic lens for understanding systemic sustainability in industrial districts. It shows convincingly that geoanthropology offers a particularly valuable and hitherto underused perspective for understanding and assessing sustainability in territorially embedded industrial contexts. The geoanthropological approach fundamentally recognizes that productive systems do not exist in the abstract vacuum of neoclassical economic models but root themselves in specific territories with distinctive geographic, cultural, historical, and institutional characteristics. This embeddedness is not merely contextual or decorative, but constitutive: it shapes possibilities, constrains trajectories, and generates both opportunities and constraints that universalist approaches fail to capture fully.

The geoanthropological analysis of the Italian ceramic district identified and structured seven fundamental dimensions that capture the multifaceted complexity of systemic sustainability in this context: resource consumption, production dynamics, innovation, environmental impact, social impact, market dynamics, and economic impact. In the article, each of these dimensions is analyzed in depth, showing how they intertwine with challenges arising from high material and energy intensity, technological and organizational transformation of the sector, international competitive pressures, and the district's economic and social importance to its territory.

The identification of these seven factors is not an arbitrary taxonomic exercise but emerges from the recognition that systemic sustainability can only be understood by considering multiple dimensions simultaneously, interacting through complex feedback loops. Improvements in innovation can drive environmental efficiency and market competitiveness, but may also generate social disruption if firms fail to manage employment and skills transitions adequately. Investments in energy efficiency can improve environmental performance and reduce operating costs, but require significant upfront capital that may be difficult to mobilize in contexts of compressed margins. These interdependencies underline the need for genuinely systemic approaches that move beyond partial optimization of isolated dimensions.

The contingency analysis developed in the first article further shows how historical events and external shocks, such as changes in Italian industrial policy, the 2008-2009 economic and European debt crises, or the COVID-19 pandemic, have differentially affected these sustainability dimensions. These disruptions forced the district to restructure, in some cases accelerating the adoption of more efficient technologies and more advanced business models, while at the same time revealing structural vulnerabilities and dependence on specific markets and distribution channels. From this perspective, the district's historical behavior illustrates incipient forms of systemic agility, understood as a collective capacity for reconfiguration in the face of shocks. This incipient agility foreshadows the dissertation's later emphasis on the articulation between sustainability and organizational agility.

The proposal for a systemic sustainability index derived from geoanthropological insights aims to operationalize the abstract concept of systemic sustainability into a pragmatic metric for measuring, comparing, and monitoring performance over time. This index seeks to capture not only absolute levels in each dimension, but also balance and coherence across dimensions, recognizing that genuine sustainability does not consist in maximizing one dimension at the expense of others, but in reaching balanced configurations in which all dimensions achieve satisfactory levels.

Finally, the first article offers a forward-looking reflection on the possible deployment of an Industry 6.0 paradigm, aiming to explore the flexibility of the conceptual frameworks developed in the face of still-emerging technological scenarios. Rather than offering closed predictions, this reflection underscores the need to design systemic sustainability approaches capable of adapting to deep transformations in productive systems, thereby contributing to the main research question of how to conceptualize and analyze systemic sustainability in complex manufacturing production systems.

5.1.2 Second article: SYMΞX framework and thermoeconomic grounding

The second article focuses on developing an innovative theoretical framework that integrates thermoeconomic principles into management sciences, leading to the SYMΞX framework. The article's main conceptual contribution is the rigorous physical grounding of sustainability. For decades, dominant approaches to corporate sustainability have been predominantly economic-financial, socio-organizational, or ethical, often lacking any anchoring in the physical realities that govern all resource transformation processes. Thermodynamics - particularly the Second Law, which establishes the fundamental irreversibility of real processes and the inevitable degradation of exergy into entropy - provides such an anchor.

Within this perspective, the concept of exergy is particularly appropriate for assessing sustainability because it captures the quality of energy and resources rather than their quantity alone. Unlike total energy, which can remain constant even as it degrades, exergy reflects the fraction that can be harnessed to perform useful work. From this viewpoint, we can regard production processes as transformation chains in which each stage irreversibly destroys exergy, and this destruction serves as a direct indicator of inefficiency and pressure on natural resources. Incorporating this exergy-based logic into management enables going beyond simple energy or financial balances and evaluating the extent to which a system organizes the use of its resources in a physically sustainable way.

Extending exergy analysis from traditional energy systems to broader business management constitutes one of SYMΞX's core conceptual innovations. The article proposes interpreting different organizational resources - raw materials, human capital, technological capabilities, social capital - as analogous to "reservoirs" of exergy that organizations can mobilize efficiently. This reading reframes organizational performance by asking how much each process degrades the "quality" of resources and which productive configurations minimize that degradation. Although this extension requires further conceptual development and empirical validation, it opens a fertile space to rethink efficiency and sustainability from a physically grounded organizational perspective.

The SYMΞX framework does not aim to replace existing sustainability approaches, such as Life Cycle Assessment, triple bottom line accounting, or ESG reporting. Instead, it complements them by making explicit the thermodynamic foundations of production processes. Integrating SYMΞX with these instruments can reveal, for example, that improvements that appear relevant in conventional indicators become less significant when analyzed exergically or, conversely, that interventions that seem marginal from a purely financial perspective substantially reduce exergy destruction. In this way, SYMΞX adds an interpretive layer that supports a more comprehensive assessment of the sustainability of business decisions.

On this basis, SYMΞX calls for the development of multidimensional exergy-based performance indicators that simultaneously integrate environmental, economic, social, and technological dimensions. Such indicators make it possible, for instance, to relate the destruction of natural exergy to the economic value generated, to examine equitable access to high-quality resources, or to evaluate the extent to which technological innovation reduces thermodynamic inefficiencies. Although the proposal does not yet specify a closed set of metrics, it provides the principles needed to design indicator systems consistent with the physical limits of productive systems.

A key feature of SYMΞX is its flexibility and adaptability. Rather than offering a rigid set of indicators valid for any organization, the framework proposes general principles that organizations can tailor to specific sectoral and organizational contexts. In this way, an energy-intensive chemical company, a light manufacturing firm, or an advanced service provider can design different configurations of exergy-based metrics, maintain conceptual coherence, and adapt tools to their operational realities and specific sustainability challenges.

Finally, the article highlights the ethical implications of the proposed approach. By making visible the real costs in terms of destruction of physical resources, SYMΞX challenges decisions based solely on short-term financial criteria that tend to externalize environmental and social impacts. Explicitly showing how much natural capital and resource quality are lost under each decision alternative can reorient organizational choices toward more responsible configurations, aligning the pursuit of efficiency with the need to preserve the material foundations on which economic activity depends. Taken together, this second article makes a substantial contribution to answering the question of how thermoeconomic principles can be integrated into management to evaluate resource-use efficiency and organizational sustainability from a physically grounded perspective, and it provides a solid basis for designing productive configurations that are both sustainable and compatible with the agility required in complex environments.

5.1.3 Third article: data-driven SO-LCA methodology

The third article addresses the objective of developing a data-driven methodology for Organizational Social Life Cycle Assessment that reduces subjectivity and improves comparability of results across organizations and contexts. It develops the methodological component that completes the integrative view of systemic sustainability, using a rigorous, quantitative, data-driven approach to assess the social dimension. This dimension has traditionally been the least developed within the sustainability paradigm, partly because translating complex social phenomena into operational, comparable indicators is difficult, and partly because of heterogeneous cultural and institutional contexts and the scarcity of systematic data. The article tackles this gap by proposing an approach that combines advanced statistical tools with an indicator design aligned with leading international standards on social sustainability.

From a methodological standpoint, the proposal rests on two main technical pillars: Principal Component Analysis (PCA) and sigmoid normalization. PCA enables the identification of underlying dimensions in complex sets of social indicators, reducing dimensionality without losing relevant information and revealing latent structures that are not evident in univariate analyses. Sigmoid normalization, in turn, addresses the challenge of integrating indicators with different units, ranges, and directions of preference, transforming them onto comparable scales that facilitate aggregation and the construction of synthetic indices of social sustainability.

In terms of alignment with reference frameworks, the methodology explicitly aligns with UNEP guidelines for Social Life Cycle Assessment (S-LCA) and with emerging ESG reporting requirements, particularly in the European context marked by the Corporate Sustainability Reporting Directive (CSRD) and new due diligence initiatives on human rights and working conditions along the supply chain. In this way, the approach is not only academically relevant but also directly useful for organizations that must respond to an increasingly demanding regulatory environment in the social domain.

Empirically, the methodology is validated through an in-depth case study in a firm from the Italian ceramic sector, using primary internal organizational data. This application enables the identification of a set of particularly critical social dimensions for the analyzed context, including working conditions, occupational health and safety, skill development, diversity and inclusion, engagement with the local community, and respect for human rights in the supply chain. The case shows that the methodology can be implemented in a real industrial setting and adapted to the specific characteristics of each sector.

From an applied perspective, the most relevant outcome is the methodology's ability to detect gaps between stakeholder expectations and organizational reality, as well as social hotspots that require priority attention. This diagnostic function helps direct improvement efforts toward areas with the greatest potential impact, avoiding the dispersion of resources into marginal initiatives. When embedded within Industry 5.0 frameworks, the proposed data-driven SO-LCA not only supports regulatory compliance and transparency in social performance but also reinforces the human-centric foundations on which resilience and organizational agility in complex supply chains depend.

Taken together, the three articles carry out the research program outlined in the dissertation's introduction. The geoanthropological approach in the first article aims to analyze systemic sustainability from a territorial and contextual perspective. The SYMΞX framework in the second article addresses integrating thermoeconomic principles into the assessment of efficiency and organizational sustainability. The data-driven SO-LCA methodology in the third article operationalizes the social dimension of sustainability. Empirical validation in the Italian ceramic district fulfills the applied objective of demonstrating the practical viability of the proposed frameworks. At the same time, the joint reading of the three blocks provides the basis for the integrative objective of articulating a holistic approach to systemic sustainability in complex manufacturing supply chains, while remaining compatible with high levels of organizational agility.

5.2 Connections between the publications in the compendium

5.2.1 Systemic sustainability as an integrative concept

The three articles included in this doctoral dissertation are not isolated contributions developed independently but integral components of a coherent research program strategically designed to address different facets of a complex phenomenon: systemic sustainability in advanced manufacturing contexts and its management in an industrial landscape undergoing profound paradigm shifts.

In this thesis, systemic sustainability functions as the integrative concept that unifies the three articles. It is conceived not as the sum of three independent pillars (economic, environmental, and social) but as an emergent property of complex systems that we can only understand by examining their interconnections, synergies, trade-offs, and co-evolutionary dynamics. From this perspective, systemic sustainability is simultaneously holistic, contextual, dynamic, multi-level, and multi-stakeholder, as it explicitly incorporates interdependencies among dimensions, the territorial and historical specificity of productive systems, their evolution over time, and the diversity of actors involved, including shareholders, employees, supply chain partners, local communities, and future generations.

5.2.2 Conceptual and methodological complementarity

Each article addresses systemic sustainability from a specific angle that synergistically complements the others. The first article provides a broad strategic vision and a transdisciplinary conceptual framework through the geoanthropological lens, recognizing the territorially and contextually embedded nature of productive systems. This perspective is crucial because it prevents the adoption of universalist approaches that overlook how geographical, cultural, and historical specificities deeply shape the forms sustainability can take and the trajectories that are feasible or desirable in particular contexts.

The second article offers the physical grounding and conceptual foundations for efficiency measurement tools through the thermoeconomic perspective and the SYMΞX framework. This contribution is essential because it anchors sustainability in physical realities governed by inescapable thermodynamic laws, moving beyond purely economic-financial or discursive approaches that can lose contact with the material constraints that limit what is physically possible. The recognition that all resource transformation processes are subject to the Second Law of Thermodynamics and irreversibly degrade exergy provides a universal and objective basis for evaluating efficiency and sustainability.

The third article completes the picture by incorporating the social dimension and provides operational, data-driven methodologies that enable systematic assessment of social impacts with a level of rigor comparable to that achieved in environmental assessment. This contribution is crucial because the social dimension, often relegated to third place after economic and environmental concerns, is in fact constitutive of systemic sustainability: productive systems that are socially unsustainable, characterized by labor exploitation, community exclusion, or human rights violations, cannot be considered genuinely sustainable regardless of their environmental or economic performance.

The methodological complementarity among the articles is evident and strategically designed. The first and second articles emphasize theory building through exhaustive literature review, conceptual synthesis, and abductive reasoning aimed at finding the best explanations for observed phenomena. This emphasis on theoretical construction is appropriate given the nature of their contributions: developing new conceptual frameworks that integrate previously disconnected domains primarily requires rigorous theoretical work. The third article complements this with rigorous empirical validation through an in-depth case study and quantitative analysis using advanced statistical techniques. Such validation is essential to demonstrate that the conceptual frameworks developed are not merely speculative exercises but can be operationalized in real-world contexts, generating valuable insights.

The integration of qualitative and quantitative approaches across the three articles reflects the recognition that complex phenomena such as systemic sustainability require methodological pluralism. Qualitative methods are essential for understanding meanings, interpreting contexts, and building theory from rich cases. Quantitative methods are necessary to identify patterns in data, validate relationships, and generate generalizations that transcend specific cases. The strategic combination of both approaches across the three articles provides a more comprehensive view than could be achieved through any single methodological approach.

The operational transdisciplinarity demonstrated across the three articles is not merely rhetorical. Each article genuinely integrates concepts and methods from multiple disciplinary domains in ways that transcend their original identities. The first article brings together geoanthropology, management sciences, innovation studies, and complex systems analysis in a framework that inherits elements from all these traditions yet belongs to none of them. The second article fuses thermoeconomics, organizational theory, and sustainability management into the SYMΞX framework, which constitutes a novel conceptual synthesis. The third article combines life cycle assessment, advanced statistics, stakeholder theory, and sustainability management into a methodology that leverages the strengths of each domain.

The logical progression from broad conceptual frameworks to concrete operational tools runs coherently through the three articles. This progression is not merely temporal but logical, in the sense that each level requires and benefits from the previous ones. The strategic framework provided by the geoanthropological approach in the first article establishes the broad vision that guides subsequent developments, answering the fundamental question of from which perspective sustainability should be understood in complex industrial contexts. The theoretical grounding offered by SYMΞX in the second article addresses how efficiency and sustainability can be measured on a sound physical basis, providing conceptual foundations for metric development. The practical operationalization in the third article shows how organizations can systematically assess the social dimension of sustainability, translating abstract principles into concrete, applicable procedures.

5.2.3 The Italian ceramic district as a unifying context

The Italian ceramic district serves as a unifying empirical context that meaningfully connects the three articles. The first article uses the district as a paradigmatic case to apply the geoanthropological analysis, exploring how specific territorial factors - such as geographic concentration, the district's historical trajectory, labor market configuration, networks of specialized suppliers, and the role of sectoral institutions - shape its sustainability trajectories. Although the second article develops a general theoretical framework that does not focus on a specific sector, its implications for energy-intensive industries such as ceramics are evident and explicitly discussed. The third article closes the loop by empirically validating the SO-LCA methodology precisely in a firm in the Italian ceramic sector, using real organizational data that reveal both challenges and opportunities specific to the sector in terms of social sustainability.

This deliberate convergence on a common empirical context enables a deep, multifaceted understanding of a specific case from complementary perspectives, demonstrating how the different proposed frameworks can be applied and integrated in a real setting characterized by genuine complexity. The ceramic district thus emerges not as a passive "object of study," but as a complex system whose in-depth understanding requires the multiple lenses provided by the three articles.

5.2.4 Alignment with Industry 5.0, Industry 6.0, and supply chain management

The three articles also align coherently with the emerging Industry 5.0 paradigm and its projection towards Industry 6.0. At the Industry 5.0 level, they help to operationalize its three fundamental pillars in manufacturing supply chains. First, they advance the human-centric pillar: the first article foregrounds human-territory interactions in production systems; the second proposes metrics that move beyond purely techno-economic logics by explicitly recognizing human value; and the third places social assessment at the core of corporate sustainability. Second, they deepen the sustainability pillar by treating sustainability as (i) a territorial and contextual phenomenon, (ii) a matter of physical efficiency in resource use, and (iii) a social dimension that can be evaluated systematically. Third, they reinforce the resilience pillar by analyzing how the district responds to disruptions (Article 1), arguing that exergy efficiency enhances resilience by optimizing resource use (Article 2), and showing how stakeholder engagement strengthens social legitimacy and organizational resilience (Article 3). From the perspective of Industry 6.0, the joint contribution of the three articles lies in integrating these pillars into a broader systemic sustainability logic, where value creation, adaptability, and resilience are assessed not only within individual firms, but also across supply chains, territories, stakeholders, and natural systems.

Finally, the three articles converge in their direct relevance for managing complexity in supply chains, the central theme of this doctoral dissertation. The first article provides conceptual tools for understanding the systemic and territorial nature of supply chains, moving beyond simplistic linear views that reduce them to sequences of transactions between independent actors. The second article presents metrics based on physical exergy flows that enable tracing efficiency across complex supply chains and identify points of excessive exergy destruction as opportunities for improvement. The third article addresses the social dimension of supply chains, which is increasingly critical in contexts of mandatory regulatory due diligence and pressures from conscious consumers who demand transparency regarding working conditions and respect for human rights at all levels of the chain.

Taken together, the three articles provide a comprehensive conceptual and methodological toolkit for organizations seeking to navigate the complexity of globalized supply chains while advancing toward more sustainable, resilient, and human-centric business models. This toolkit is not a rigid set of universal prescriptions, but a flexible system of principles, frameworks, and tools that can be adapted to diverse contexts while maintaining fundamental conceptual coherence. It also enables supply chain agility to be conceived as a dynamic capability aligned with systemic sustainability, rather than in tension with it.

5.3 Theoretical and practical implications

The findings of this doctoral research generate significant implications that go beyond the purely academic domain and extend to business management, supply chains, public policy design, and education.

5.3.1 Theoretical implications

At the theoretical level, this research substantially advances systemic sustainability theory by rigorously operationalizing a concept that often remains abstract in the academic literature. While systems thinking applied to sustainability has produced valuable conceptual insights into interconnections, feedback loops, and emergent behaviors, researchers have rarely translated these insights into concrete tools for analyzing, measuring, and managing sustainability in real organizational contexts.

This dissertation helps close that gap by developing three frameworks that operationalize systemic sustainability from complementary perspectives: territorial-contextual through the geoanthropological approach, physical-thermodynamic through SYMΞX, and social-quantitative through the data-driven SO-LCA methodology.

The multi-level integration across the three articles shows how the research coherently combines perspectives from multiple scales. Systemic sustainability does not reside exclusively at the organizational, territorial, or supply chain levels; rather, it emerges from complex interactions among all three. An individual organization may improve its environmental performance through efficiency investments, but its systemic sustainability also depends on how it is embedded in its territory, how it interacts with its supply chain, and how it contributes to broader sectoral dynamics. This multi-level view has important implications for organizational theory, as it challenges perspectives that treat organizations as independent, self-contained units of analysis.

The interdisciplinary grounding established through conceptual bridges between traditionally separate domains constitutes another important theoretical contribution. Geoanthropology has rarely engaged in dialogue with business management; thermoeconomics has primarily developed within energy engineering; and social life-cycle assessment has remained relatively marginal in management research. By demonstrating how this dissertation productively integrates concepts and methods from these domains with management and sustainability theories, this dissertation illustrates the value of genuinely transdisciplinary approaches that overcome the disciplinary fragmentation characteristic of contemporary academia.

The enrichment of organizational theories through systemic sustainability concepts manifests in multiple ways. The notion of organizational performance is broadened beyond traditional financial metrics to incorporate physical efficiency in resource use, balance across multiple sustainability dimensions, and contribution to the sustainability of broader systems (territorial, sectoral, and supply chain). This broadening is not merely additive, simply adding non-financial indicators to financial ones, but transformative. It questions what organizational performance fundamentally means in the context of planetary boundaries, social pressures, and accelerated technological change.

Stakeholder theory is enhanced through systematic methodologies for identifying and assessing social impacts on different stakeholder groups. While stakeholder theory has convincingly argued that organizations must consider the interests of multiple actors beyond shareholders, the tools for operationalizing this consideration have been less well developed. The data-driven SO-LCA methodology proposed in the third article provides such a tool, enabling systematic identification of which stakeholders are most affected by organizational operations, in which dimensions, with what magnitude, and how stakeholder perceptions compare with organizational reality, revealing possible expectation gaps (Mahajan et al., 2023).

Implications for theories of organizational agility and resilience emerge from the recognition that these capabilities are not merely technical or operational attributes but depend fundamentally on systemic sustainability. Organizations that systematically degrade their natural, social, or human capital in the name of short-term efficiency may appear agile in the present but become fragile in the long term, when degraded resources become scarce or when eroded social legitimacy generates resistance and conflict. Conversely, organizations that invest in systemic sustainability develop deeper forms of resilience through diversified resource bases, robust relationships with multiple stakeholders, and strong capacity to adapt to changing conditions.

The contribution to the conceptual and methodological development of the Industry 5.0 paradigm is particularly relevant given its emergent nature. Much of the existing literature on Industry 5.0 remains at the visionary or programmatic level, articulating broad principles of human centricity, sustainability, and resilience without providing detailed guidance on how to operationalize them. This research contributes to consolidating the paradigm by giving its principles concrete substance through practical frameworks. The forward-looking exploration of Industry 6.0, although still emerging, feeds debate on possible industrial futures and helps ensure that the frameworks developed remain sufficiently flexible to accommodate future transformations (Barata & Kayser, 2023; Ghobakhloo et al., 2023).

5.3.2 Implications for business management and supply chains

For business management and supply chain management, the practical implications of this research are multiple and directly relevant to various stakeholders.

For managers and sustainability professionals in manufacturing organizations, the frameworks developed in this thesis offer practical tools that can be adopted and adapted to specific contexts. The geoanthropological framework provides a lens for understanding how territorial and contextual factors shape sustainability possibilities and trajectories, helping to design strategies that respect local specificities rather than applying universal "best practices." The SYMΞX framework supplies a conceptual basis for developing physically grounded resource-efficiency metrics, complementing traditional financial indicators with thermodynamic perspectives that reveal performance dimensions invisible to conventional accounting. The data-driven SO-LCA methodology outlines concrete procedures for systematically assessing social impacts, generating quantitative evidence for regulatory compliance, and identifying opportunities for improvement and strategic differentiation.

The guidance for implementing Industry 5.0 provided by this research is particularly valuable at a time when many organizations are exploring how to evolve from Industry 4.0 models centered on efficiency toward more balanced models that integrate human centricity, sustainability, and resilience. The proposed frameworks suggest how this integration can be achieved operationally rather than merely at the level of rhetoric.

The diagnostic tools enabled by the frameworks allow organizations to systematically identify strengths on which to build, weaknesses that require attention, gaps between current performance and aspirations or requirements, and hotspots where negative impacts are particularly severe, or risks are especially high. This systematic diagnostic capability is essential for prioritizing limited resources toward interventions with the greatest potential impact.

Support for ESG reporting provided by the developed methodologies, particularly the data-driven SO-LCA, has immediate practical relevance in the European regulatory context, where transparency requirements are expanding rapidly. The Corporate Sustainability Reporting Directive will significantly increase the number of firms required to report comprehensively on sustainability, and various due diligence directives will oblige companies to monitor and report on human rights and working conditions in their supply chains. The proposed methodologies facilitate the generation of the required information with rigor and comparability (European Commission, 2021).

For supply chain managers, the implications are especially significant, as supply chain sustainability has become a central concern. Supply chain managers can use these frameworks to evaluate the sustainability of suppliers and partners across multiple dimensions beyond price and quality. The exergy-based approach enables tracing efficiency in transformations along complex chains, identifying where in the chain excessive exergy destruction occurs, thereby representing both economic inefficiency and environmental unsustainability. The SO-LCA methodology facilitates compliance with emerging social due diligence requirements by establishing systematic procedures for assessing working conditions and human rights across multiple tiers of the supply chain.

Insights on systemic sustainability also inform strategies for building more resilient supply chains. These strategies include diversifying suppliers to reduce dependence on single vulnerable sources, deep collaboration with key suppliers to build trust and joint responsiveness in times of crisis, radical transparency to increase risk visibility along the chain, and targeted investment in supplier capabilities to strengthen the entire network.

5.3.3 Implications for public policy design

For policymakers, this research generates relevant insights for the design of industrial and sustainability policies, especially in the context of mature industrial districts and resource-intensive sectors. The geoanthropological approach highlights the fundamental importance of considering territorial specificities in policy design, avoiding standardized models that ignore the fact that what works in one context may be inadequate or even counterproductive in another. Effective policies to promote sustainability in mature industrial districts such as the Italian ceramic cluster must consider historical trajectories, accumulated capabilities, institutional networks, and specific production cultures.

The methodologies developed here can inform the design of sustainability regulatory frameworks, including the definition of reporting requirements that are both comprehensive and feasible, the establishment of sustainability standards that recognize sectoral and contextual differences while maintaining rigor, and the development of monitoring and enforcement mechanisms that rely on systematic quantitative data rather than purely qualitative or discretionary assessments.

Findings on the ceramic district provide concrete lessons on how to facilitate transitions toward sustainability in traditional sectors that face significant challenges related to material and energy intensity, international competitive pressures, and long historical trajectories that generate organizational and institutional inertia. Successful transitions require combinations of regulation that set minimum mandatory thresholds, incentives that lower financial barriers to sustainability investments, support for innovation through funding for research and development, facilitation of sector-level collaboration to share knowledge and resources, and skills development programs that prepare the workforce for technological and organizational transformations.

The effective promotion of Industry 5.0 requires policies that go beyond the mere diffusion of digital technologies to address, in an integrated way, its three core dimensions: human centricity, sustainability, and resilience. The frameworks proposed in this dissertation identify metrics for monitoring progress along these dimensions and outline how to design policies that align incentives with Industry 5.0 objectives rather than solely with production efficiency.

For the ceramic sector specifically, empirical validation generates sector-level knowledge that supports diagnosis, benchmarking, roadmap development, and sustainability-based competitive differentiation. It helps identify specific challenges and opportunities, allows individual firms to assess their performance relative to the sector, highlights priority areas for collective intervention, and informs differentiation strategies, particularly valuable in international markets where consumers and institutional buyers increasingly value robust sustainability credentials.

5.3.4 Implications for education and training

Although education and training are not the central focus of this research, their implications warrant explicit attention. Courses in industrial engineering, operations management, supply chain management, and corporate sustainability should explicitly address concepts such as systemic sustainability, exergy-based management analysis, and Industry 5.0. Training providers can also use the tools developed in this dissertation in continuing professional education programs for practitioners who need to update and expand their competencies.

The transdisciplinary approach exemplified in this work also highlights the need to move beyond compartmentalized educational programs and to train professionals who can integrate technical, managerial, social, and environmental perspectives when addressing the complex challenges of sustainability and industrial transformation.

6 GENERAL CONCLUSIONS

This doctoral dissertation has explored systemic sustainability as an innovative organizational paradigm for managing complexity in manufacturing supply chains during the transition toward Industry 5.0 and its projected evolution toward Industry 6.0. Through three complementary articles that integrate geoanthropological, thermoeconomic, and data-driven perspectives, the research has developed and validated theoretical-methodological frameworks that advance academic knowledge and support managerial practice in sustainability.

6.1 Main contributions of the research

From the perspective of the research questions Q1-Q5 defined in Section 1.3.4, this thesis provides articulated answers that combine conceptual, methodological, and empirical results, as summarized below.

6.1.1 Conceptual and theoretical contributions

At the conceptual-theoretical level, the thesis significantly advances the conceptualization of systemic sustainability as a paradigm that transcends the limitations of the traditional triple bottom line and coherently integrates organizational agility into the management of complex supply chains. Rather than conceiving sustainability as three independent pillars to be optimized separately, systemic sustainability recognizes the deeply interconnected nature of the economic, environmental, social, and technological dimensions.

This systemic view incorporates the recognition that organizations are territorially embedded in specific contexts that condition their possibilities and trajectories; a rigorous physical grounding in thermodynamic principles that govern all processes of resource transformation; the centrality of the human factor and of relationships with multiple stakeholders; an orientation toward long-term resilience rather than merely short-term efficiency; and the need for continuous adaptation to changing technological, regulatory, and social conditions.

The establishment of an innovative conceptual bridge between thermoeconomics and management science constitutes a particularly original theoretical contribution. These two domains have historically evolved in parallel with limited interaction. Thermoeconomics has developed mainly in the context of energy systems and specific industrial processes, whereas management sciences have largely adopted economic–financial, socio-organizational, or strategic perspectives without explicitly considering fundamental physical constraints. This research shows that thermodynamic principles - particularly the concept of exergy as a measure of the quality of energy and resources - can substantially enrich organizational theories of performance, efficiency, and sustainability. The SYMΞX framework operationalizes this integration by proposing the use of exergy analysis not only for conventional energy flows but also, more broadly, for diverse organizational resources. This perspective reveals dimensions of efficiency and sustainability that remain invisible in conventional metrics.

The enrichment of the emerging Industry 5.0 paradigm with substantive conceptual and methodological content represents another important theoretical contribution. Given that Industry 5.0 is still in an early stage of conceptual development and practical adoption, there is a pressing need for frameworks that translate the abstract principles of human centricity, sustainability, and resilience into concrete implementation guidance. This research provides such content through three complementary frameworks that operationalize these principles from territorial-contextual, physical-thermodynamic, and social-quantitative perspectives. Extending this logic, the prospective exploration of Industry 6.0 contributes to current debates on industrial futures by framing systemic sustainability as a broader organizational strategy for value creation, adaptability, and resilience, thereby clarifying how the expected performance of industrial systems may evolve beyond operational efficiency and ESG-oriented value creation.

The demonstration of the value of genuinely transdisciplinary approaches constitutes a higher-order contribution whose implications extend beyond this specific research project. In an academic context often characterized by hyper-specialization and disciplinary fragmentation, this thesis illustrates how the deep integration of perspectives from diverse domains can generate insights and solutions that would not emerge from mono-disciplinary approaches. The operational transdisciplinarity demonstrated here is not merely a juxtaposition of multiple perspectives but a conceptual synthesis that creates new frameworks that inherit elements from various traditions while transcending their original disciplinary identities.

Taken together, these conceptual contributions directly support an answer to the main research question Q1 by offering an operational conceptualization of systemic sustainability in complex manufacturing systems, and to question Q5 by showing how this conceptualization links organizational agility with the Industry 5.0 paradigm in the management of supply chains.

6.1.2 Methodological and instrumental contributions

At the methodological-instrumental level, this research develops three tool systems that operationalize systemic sustainability from complementary angles.

The geoanthropological framework translates abstract concepts from geoanthropology - traditionally applied to the study of populations, migrations, and human-environment relations - into analytical tools specifically designed for industrial contexts. This framework enables a systematic analysis of how territorial, cultural, and historical factors condition the sustainability of production systems, identifying seven key dimensions spanning resource consumption, social impacts, and market dynamics. The ability to conduct contingency analyses that explicitly consider historical events and to develop synthetic indices of systemic sustainability provides pragmatic tools for diagnosis and monitoring.

The SYMΞX framework creates an innovative management system grounded in exergy analysis that adapts to diverse organizational and sectoral contexts. Its core innovation lies in extending the application of thermoeconomic concepts beyond traditional energy systems to broader business management, arguing that resource-use efficiency requires assessing not only quantities but, fundamentally, thermodynamic quality. This framework enables the development of performance indicators that integrate environmental dimensions related to the destruction of natural exergy, economic dimensions evaluating exergy productivity, social dimensions considering equitable access to high-quality resources, and technological dimensions assessing innovation capacity in efficiency. The emphasis on flexibility in the framework's design recognizes that contexts vary widely and that rigid, universal prescriptions would be inadequate.

The data-driven SO-LCA methodology developed in the third article represents a significant methodological advance in assessing social sustainability. Whereas previous social assessments have suffered from excessive subjectivity, heterogeneous criteria, and limited comparability, the proposed methodology strategically integrates advanced statistical techniques to mitigate these issues. Principal Component Analysis enables the identification of underlying dimensions within complex sets of social indicators, revealing latent structures that are not evident in superficial analyses. Sigmoid normalization addresses the technical challenge of integrating heterogeneous indicators with different units, ranges, and directionalities by transforming them onto comparable scales. The explicit alignment with UNEP international guidelines and emerging ESG reporting requirements ensures the methodology's practical relevance in an evolving regulatory environment.

The development of synthetic sustainability indices that capture multidimensionality and interactions constitutes a transversal methodological contribution across the three articles. These indices seek to overcome limitations of approaches that present long batteries of stand-alone indicators without integration, which hinders interpretation and communication. The proposed composite indices aggregate information in ways that preserve essential complexity while facilitating comprehensive evaluation, comparison between organizations or contexts, monitoring of temporal evolution, and effective communication with diverse stakeholders.

From the standpoint of the research questions, the geoanthropological framework contributes primarily to Q2 by providing tools to analyze systemic sustainability while explicitly incorporating the territorial embeddedness of industrial districts; the SYMΞX framework responds directly to Q3 by proposing a rigorous way to integrate thermoeconomic principles into management; and the data-driven SO-LCA methodology is the key instrument for addressing Q4 by designing a data-based procedure that reduces subjectivity in social assessment. All three also reinforce the answer to Q1 by providing concrete instruments to operationalize systemic sustainability.

6.1.3 Empirical and sectoral contributions

At the empirical-applied level, rigorous validation in the Italian ceramic district demonstrates the practical feasibility of the proposed frameworks and generates valuable sector-specific knowledge. The ceramic district constitutes a particularly rich case, characterized by significant economic relevance, systemic complexity involving multiple actors and institutions, severe sustainability challenges related to material and energy intensity, and the coexistence of centuries-old tradition with advanced technological innovation. Applying the three frameworks to this specific context reveals both distinctive sectoral challenges and lessons that are potentially transferable to other manufacturing sectors undergoing similar transitions toward sustainability.

The research identifies a set of ceramic-sector challenges related to the high energy and material intensity of its processes, the need for robust management of emissions and waste, and the social transformations associated with digitalization and automation, which demand new skill sets and careful management of labor transitions. These challenges are not unique to the ceramic sector but reflect issues shared by many traditional manufacturing industries that are intensive in materials and energy.

The potentially transferable lessons include the recognition that sustainability transitions in mature sectors require approaches that respect historical trajectories and accumulated capabilities rather than imposing radical disruptions that destroy value; the importance of sectoral collaboration to share innovation costs, develop common standards, and create economies of scale in the adoption of sustainable technologies; the crucial role of intermediary institutions such as industry associations, technology centers, and territorial development agencies in facilitating coordination and knowledge diffusion; and the need for public policies that combine regulation establishing minimum mandatory standards with incentives that reduce financial barriers to sustainability investments.

Empirically, the application of these frameworks to the Italian ceramic district contributes to Q2 by analyzing systemic sustainability in a concrete and territorially embedded manufacturing district; reinforces Q4 by validating in practice the data-driven SO-LCA methodology; and provides relevant evidence for Q1 and Q5 by showing how the combination of these approaches can inform decision-making in a real production system exposed to high levels of complexity and the need for competitive agility.

6.1.4 Integrative synthesis of the contributions

The core integrative contribution, which synthesizes all previous results, is to provide a coherent and comprehensive system of conceptual and methodological frameworks for the operational implementation of systemic sustainability. This system is not simply the sum of three independent contributions, but an integrated architecture in which the components reinforce each other and create synergies. The geoanthropological framework establishes the conceptual foundations by recognizing the territorial and contextual nature of sustainability; the SYMΞX framework provides a rigorous physical basis by anchoring sustainability in thermodynamic realities; and the data-driven

SO-LCA methodology develops validated operational tools for the social dimension, which is often less developed.

The integration of these three components simultaneously addresses the economic, environmental, social, and technological dimensions rather than treating them in a fragmented way; connects the micro level of the individual organization, the *meso* level of the industrial district and territory, and the macro level of the supply chain and sectoral systems; provides both diagnostic capabilities, by identifying the current state, and orientation for continuous improvement and strategic transformation; and balances conceptual rigor with practical applicability.

In this way, the integrated system of frameworks developed in the thesis provides a structured answer to the main question Q1: how to conceptualize and analyze systemic sustainability in an operational way within complex manufacturing systems. It also addresses integrative question Q5 by showing that combining geoanthropological, thermoeconomic, and data-driven social perspectives can guide the joint management of systemic sustainability and agility in supply chains aligned with the principles of Industry 5.0.

6.2 Relationship with the research questions (Q1–Q5)

Q1. *How can systemic sustainability in manufacturing production systems be conceptualized and analyzed in ways that are operationally useful for decision-making in complex supply chains?*

The thesis responds to Q1 by developing an integrated conceptualization of systemic sustainability in Part I (introduction and theoretical framework) and Part III (synthesis, discussion, and conclusions) and translating it into operational frameworks distributed across the three articles. The geoanthropological approach in Article 1 provides a territorial and multi-level reading of production systems; the SYMΞX framework in Article 2 incorporates a physical-thermodynamic basis for measuring resource-use efficiency; and the data-driven SO-LCA methodology in Article 3 operationalizes the social dimension with quantitative rigor. Taken together, these results constitute an analytical system that can inform strategic and operational decision-making in complex supply chains.

Q2. *How can systemic sustainability be analyzed in manufacturing industrial districts while explicitly incorporating their territorial embeddedness and interdependencies with the surrounding environment?*

Article 1 primarily addresses Q2 by applying the geoanthropological approach to the Italian ceramic district. The identification of seven key dimensions of systemic sustainability, the historical contingency analysis, and the design of the systemic sustainability index jointly capture, in a structured way, the interdependencies among production, territory, community, and markets. The empirical application to the Sassuolo district offers a concrete example of how to analyze systemic sustainability in a territorially embedded manufacturing industrial district.

Q3. *In what ways can thermoeconomic principles be integrated into management sciences to evaluate resource-use efficiency and organizational sustainability from a physically grounded perspective?*

Article 2 mainly addresses Q3 by formulating the SYMΞX framework as a conceptual bridge between thermoeconomics and business management. The article extends exergy analysis from traditional energy systems to broader organizational processes and decisions, and conceives physical, technological, human, and social resources as "reservoirs" of exergy whose destruction signals inefficiencies and sustainability pressures. On this basis, it proposes principles for designing exergy-based performance indicators that complement conventional economic and environmental metrics.

Q4. *How can a data-driven methodology for Social Organizational Life Cycle Assessment be designed to reduce subjectivity and improve the comparability of results across organizations and contexts?*

Article 3 develops the answer to Q4 by proposing a data-driven SO-LCA methodology that combines indicator design aligned with international standards, Principal Component Analysis, and sigmoid normalization. The application to an Italian ceramic company shows that this methodology reduces subjectivity, improves comparability, and generates robust diagnoses of social impacts across different stakeholder groups, thereby offering a practical tool for managing the social dimension of sustainability within the Industry 5.0 framework.

Q5. *To what extent does the combination of geoanthropological, thermoeconomic, and data-driven social perspectives advance integrated management of systemic sustainability and agility in manufacturing supply chains aligned with the principles of Industry 5.0?*

Part I and Part III together address the integrative question Q5 by showing how the three developed frameworks work together to manage systemic sustainability in complex supply chains without sacrificing organizational agility. The geoanthropological approach provides a systemic and territorial perspective, SYMΞX offers a physical and thermodynamic basis for improving resource-use efficiency, and the data-driven SO-LCA methodology rigorously incorporates the social dimension and stakeholder expectations. Taken together, these frameworks align the pursuit of sustainability, resilience, and human centricity, which are central to Industry 5.0, with the need to maintain dynamic capabilities for rapid adaptation in manufacturing supply chains.

7 LIMITATIONS OF THE STUDY

7.1 Methodological limitations

This work presents limitations that must be acknowledged explicitly, not as weaknesses that invalidate its contributions, but as boundaries of validity that delimit its scope and indicate necessary directions for future research.

The most significant methodological limitation concerns the extent of empirical validation of the proposed frameworks. While the third article includes robust empirical validation through an in-depth case study with primary data collection and analysis, the frameworks developed in the first two articles remain predominantly at a conceptual–theoretical level, with limited empirical testing. The geoanthropological framework is applied to the Italian ceramic district through analysis of secondary data and synthesis of existing knowledge, but does not include systematic primary data collection specifically designed to validate the framework. The SYMΞX framework is even more theoretical, with full practical operationalization still to be developed in future research. This limitation is not unusual in work that proposes new conceptual frameworks, since rigorous theory-building typically precedes extensive empirical validation. However, it does imply that conclusions regarding the practical usefulness of these frameworks should be treated as provisional until future studies provide additional validation.

The concentration of empirical validation in a single case study constitutes another important methodological limitation. Although the Italian ceramic district is a rich and complex case that allows in-depth exploration of multiple dimensions of systemic sustainability, studies in additional sectors and diverse geographical contexts would strengthen the robustness and generalizability of the findings. Sectors with different characteristics, such as those that are less energy- and material-intensive, more service-oriented, based on digital technologies, or operating in emerging economies with distinct regulatory and institutional settings, could reveal limitations of the frameworks or require substantial adaptations. The research strategy adopted here privileges depth over breadth, which is appropriate for exploratory work developing new frameworks, but it implies that extension to other contexts must be empirically verified rather than assumed.

The use of predominantly cross-sectional data that capture situations at specific points in time, rather than longitudinal data that track temporal evolution, represents another limitation. Systemic sustainability is inherently dynamic, with trajectories that evolve in response to technological, regulatory, market, and social changes. Longitudinal studies that follow organizations, sectors, or territories over extended periods would allow a better understanding of transformation dynamics, the identification of factors that facilitate or hinder transitions toward sustainability, and the assessment of the effectiveness of interventions. The contingency analyses developed in the first article do consider historical events, but through retrospective reconstruction rather than real-time prospective tracking.

The presence of residual subjectivity in the data-driven SO-LCA methodology, despite substantial efforts to minimize it, represents a further limitation. Although the use of advanced statistical techniques considerably reduces subjectivity compared with previous approaches, decisions about which indicators to include, how to weight them, and how to interpret the results inevitably involve judgments that may vary across evaluators or contexts. Future research should conduct inter-rater validation to examine whether different evaluators applying the methodology to the same context reach similar conclusions. In addition, sensitivity analyses that explore how results change under alternative methodological choices would help strengthen confidence in the methodology and its robustness.

7.2 Contextual limitations

The contextual limitations concern specific features of the case studied that may limit the immediate transferability of the findings. The focus on the ceramic sector provides valuable depth but implies that specific insights on sustainability challenges, opportunities, and strategies reflect the characteristics of this industry. Sectors with radically different sustainability profiles, such as professional services with low material intensity but high knowledge intensity, or high-tech sectors with rapid innovation cycles and accelerated obsolescence, may face distinct challenges and require distinct strategies. The transferability of the general conceptual frameworks is likely to be high, but specific applications and practical recommendations require contextualization.

The fact that the research is carried out in Italy, within a European regulatory, institutional, and cultural context, adds another layer of contextual specificity. Europe is characterized by relatively advanced sustainability regulations, labor institutions that protect workers' rights, high societal expectations regarding corporate responsibility, and greater availability of resources for sustainability investments. Applicability in non-European contexts, particularly in emerging economies where priorities may differ, resources are more limited, regulatory frameworks are less developed, and competitive pressures may be even more intense, requires careful exploration that explicitly acknowledges these fundamental differences rather than assuming automatic transferability.

The predominant focus on manufacturing also implies that the frameworks developed are oriented primarily toward organizations that transform physical materials into tangible products. Service sectors, the platform-based digital economy, primary sectors such as agriculture or mining, and hybrid business models that combine products and services exhibit sufficiently different characteristics that adaptations of the frameworks may be necessary. For example, exergy analysis is more directly applicable to transformations of materials and energy than to knowledge-intensive services, where the primary "resources" are intangible.

7.3 Temporal and scope limitations

The temporal limitations relate to the emerging and evolving nature of the industrial paradigms and regulatory frameworks that constitute the context of this research. Industry 5.0 is still a paradigm in formation, with limited large-scale practical adoption, so conclusions regarding its implementation are necessarily provisional and partially speculative. The future evolution of the paradigm, influenced by unpredictable technological, economic, social, and political developments, may diverge from currently anticipated trajectories. The rapid pace of technological change, particularly in artificial intelligence, biotechnology, nanotechnology, and quantum computing, may generate radical transformations in production systems before the proposed frameworks are widely adopted. As a result, these frameworks may require continuous updating or adaptation.

The sustainability regulatory framework is also evolving rapidly, especially in the European Union, where recent and forthcoming directives substantially modify requirements for reporting, human rights due diligence, circularity, and decarbonization. The frameworks developed in this research will need to be continuously adapted to these regulatory changes to remain practically relevant. Uncertainty about the future evolution of regulation, itself influenced by volatile political dynamics, complicates long-term planning for sustainability investments and the adoption of frameworks.

Scope limitations concern aspects of sustainability that receive limited coverage or lie outside the focus of this research. Although the systemic nature of sustainability is recognized, the analysis concentrates predominantly on the organizational and district levels, with less attention to the full global supply-chain level that cuts across territories, to national and international policy frameworks that set the broader conditions within which organizations operate, and to multi-level governance that coordinates actions across local, regional, national, and supranational scales. These dimensions are undoubtedly relevant to systemic sustainability, but are discussed more briefly in this dissertation.

Certain specific dimensions of sustainability also receive limited attention, including biodiversity and ecosystem services that underpin production systems but whose degradation often occurs far from production sites in global supply chains; intergenerational justice and responsibility toward future generations, which raise complex ethical questions about discount rates and the intertemporal distribution of costs and benefits; ethical dilemmas associated with emerging technologies such as artificial intelligence making decisions with social consequences, biotechnology modifying organisms, or neurotechnology affecting human cognition; and the political dimensions of sustainability transitions, including distributive conflicts, power struggles and hegemonic projects, and social mobilizations that drive or resist transformation.

7.4 Implementation-related limitations

The research does not address in depth the practical challenges involved in implementing the proposed frameworks in real organizational settings. Although this work intentionally designs the frameworks to be applicable, the transition from academic concepts and methodologies to day-to-day organizational practice faces multiple obstacles. These include resistance to change embedded in organizational cultures, vested interests that benefit from the status quo, and constraints on financial and human resources, particularly in small and medium-sized enterprises. There are also skills gaps where personnel lack the training needed to apply the frameworks, and systemic barriers such as misaligned incentive structures, short time horizons in financial markets, and limited sectoral coordination. Research on adoption processes, factors that facilitate or hinder implementation, and effective strategies to overcome these barriers would usefully complement the conceptual and methodological developments presented in this dissertation.

These limitations do not invalidate the contributions, but they do define the boundaries of validity and generate a substantial agenda for future research. Explicit acknowledgment of limitations is a hallmark of academic rigor and provides guidance on priority directions for extending and deepening the research program initiated in this doctoral thesis.

8 FUTURE RESEARCH DIRECTIONS

8.1 Extension, empirical validation and comparative studies

The contributions made and the limitations identified in this doctoral research suggest multiple promising avenues for future work, which can be grouped into themes without any claim to be exhaustive.

A first and immediate priority is the extension and empirical validation of the proposed frameworks. Applying the geoanthropological approach, the SYMΞX framework, and the data-driven SO-LCA methodology across a range of manufacturing sectors would enable assessment of their transferability, identification of necessary adaptations, and the generation of specialized versions optimized for specific contexts. Particularly relevant sectors include: the automotive industry, currently undergoing radical transformations toward electromobility and shared mobility; the electronics sector, characterized by rapid innovation cycles, planned obsolescence and circular economy challenges; the food sector, which connects agriculture with manufacturing and presents specific sustainability issues linked to food systems; and the textile sector, which faces severe problems regarding working conditions in global supply chains and environmental pollution. Extending the frameworks to non-manufacturing sectors such as professional services, the platform-based digital economy, tourism, or education would require significant adaptations but would also substantially broaden their applicability.

International comparative studies represent another key direction. Replicating the research in diverse geographical and cultural contexts, such as Asian countries with different industrial trajectories and varieties of capitalism, Latin American economies with specific challenges of inequality and development, African contexts where industrialization coexists with extensive informal economies, and North American countries with particular regulatory and institutional frameworks, would make it possible to explore how contextual factors shape the implementation of systemic sustainability. Such studies could reveal which principles of systemic sustainability are genuinely universal and which require substantial adaptation to specific contexts.

Longitudinal studies that track the evolution of sustainability over time constitute another important methodological need. Following cohorts of organizations, sectors, or territories over extended periods of 5 to 10 years or more would allow researchers to identify transformation trajectories, critical tipping points where systems transition between different regimes, factors that accelerate or slow transitions, and the effectiveness of specific interventions. These studies would be particularly valuable for understanding processes of systemic change, which typically unfold over time horizons longer than those of individual research projects.

Extensive quantitative validation through large-scale studies of organizations would enable statistical examination of relationships between systemic sustainability factors and organizational outcomes. Relevant research questions include whether organizations with superior performance in systemic sustainability also exhibit greater resilience to economic shocks or supply-chain disruptions; how investments in sustainability correlate with technological innovation and competitive capability; which specific configurations of sustainability practices lead to superior performance; and how the effects of sustainability on performance vary according to organizational characteristics such as size, age, sector or institutional context. Such quantitative studies would complement in-depth qualitative research, providing evidence on the generality of the relationships identified.

8.2 Theoretical deepening and connections with complex systems

Theoretical deepening constitutes another important direction. The full operationalization of the SYMΞX framework requires the development of detailed methodologies for practical implementation, including specific protocols for collecting data on material, energy, and information flows; calculation algorithms for exergy analysis that consider multiple forms of exergy; user-friendly software tools that lower technical barriers to adoption; and detailed application cases in diverse sectors that illustrate the adaptations required. Such methodological development would transform SYMΞX from a conceptual framework into a fully implementable operational system.

Exploring deeper connections between systemic sustainability and theories of complex adaptive systems, nonlinear dynamics, and emergence would open the door to the application of more sophisticated analytical tools. Agent-based simulation could be used to model the dynamics of the adoption of sustainable practices in populations of organizations, revealing how local interactions generate emergent patterns at the sectoral level. Network analysis could map collaboration networks, knowledge flows, and material dependencies in industrial districts or supply chains, identifying central actors, structural vulnerabilities, and leverage points for intervention. System dynamics modeling could capture complex feedback loops between dimensions of sustainability, exploring the long-term consequences of alternative policy or management scenarios through simulation.

8.3 Integration with circular economy, digitalization and LCSA

Exploring synergies between exergy analysis and circular economy principles is a promising theoretical-practical direction. Circular economy emphasizes keeping products, components, and materials in use for as long as possible through design for durability, repairability, remanufacturing, and recycling. Exergy analysis can reveal where, along product life cycles, valuable exergy is destroyed that could instead be preserved through alternative design choices or circular business models. This integration could generate metrics that capture circularity and thermodynamic efficiency simultaneously, overcoming the limitations of current circularity indicators, which often ignore energetic considerations.

Methodological advances in integrating digital methods represent another particularly relevant avenue, given the rapid development of Industry 4.0 and 5.0 technologies and their projection toward Industry 6.0. Future research could explore how the Internet of Things can enable continuous real-time monitoring of sustainability indicators through distributed sensors that automatically capture operational data; how artificial intelligence can analyze patterns in large data sets to identify improvement opportunities that remain invisible in conventional analyses; how blockchain can support transparent traceability in complex supply chains by recording transactions immutably; and how digital twins can simulate alternative scenarios to assess sustainability impacts before implementing physical changes. Together, these developments could radically transform sustainability management capabilities.

Machine learning applications to social assessment, using algorithms that learn patterns from historical data to predict the social impacts of decisions, identify risk hotspots before problems materialize, and generate tailored recommendations adapted to specific organizational contexts, could significantly increase the sophistication of SO-LCA. However, researchers and practitioners must carefully design these applications to avoid reproducing biases embedded in historical data and to maintain transparency about how they generate recommendations.

A further major methodological opportunity lies in the full integration of the three Life Cycle Assessment dimensions: environmental (by the well-established Environmental LCA), social (by the still-developing S-LCA), and economic (by Life Cycle Costing). Combining these with thermoeconomic perspectives in a unified, physically grounded Life Cycle Sustainability Assessment (LCSA) framework would enable truly holistic sustainability assessments of products, processes, and systems, simultaneously considering all relevant dimensions across complete life cycles.

8.4 Specific applications and sustainability governance

Specific applications in concrete contexts would generate immediate practical value. Adapting the frameworks for small and medium-sized enterprises, which constitute most of the productive fabric yet have limited technical capabilities and resources, requires simplified versions that preserve essential rigor while reducing complexity and implementation costs. Developing self-diagnosis tools, step-by-step practical guides, and accessible support services would further facilitate adoption.

Extending the systemic perspective from organizations and districts to entire global supply chains would address challenges related to traceability across multiple tiers, multi-actor governance with significant power asymmetries, and sustainability coordination when actors operate under very different regulatory and institutional frameworks. Methodologies to comprehensively map supply chains, identify sustainability risks in deep tiers, and design effective interventions would represent highly valuable contributions.

Exploring the applicability of the frameworks to the platform-based digital economy would require substantial adaptations, as its characteristics differ radically from those of traditional manufacturing. Strong network effects shape this economy, near-zero marginal costs for digital services, and specific sustainability challenges related to platform workers' conditions, market and power concentration, and algorithmic governance. However, such an extension would broaden the reach of the frameworks to sectors that are becoming increasingly important.

Research on circularity in industrial districts could investigate how actors apply circular economy principles at the territorial system level through industrial symbiosis (i.e., where one firm's waste becomes another's resource), shared infrastructures and common services, and collaborative R&D on circular innovations, leveraging the geographic proximity and dense relational networks that characterize districts.

Science–policy–practice interfaces built through participatory research that actively involve policymakers, firms, and civil society in co-designing policies to promote systemic sustainability would yield better-informed, more legitimate, and more effective policies. Rigorous evaluation of existing policy instruments, such as tax incentives for sustainability investments, support programs for Industry 5.0, and ESG regulation, should rely on quasi-experimental methods to identify their causal effects. This approach would provide solid evidence about what works, in which contexts, and why.

Exploring the social and distributive justice dimensions of sustainability transitions is both an ethical and a pragmatic imperative. This exploration should ensure that transformations do not exclude regions, sectors, or vulnerable social groups, and do not exacerbate existing inequalities. Just transitions require explicit consideration of who bears the costs and who receives the benefits, the design of compensation mechanisms for those who lose out, and genuine participation of affected actors in policy design.

Finally, research on sustainable business models that examine how principles of systemic sustainability can be integrated into business model innovation would provide practical guidance for both entrepreneurs and established firms. Such models seek to capture and distribute value beyond the exclusive maximization of shareholder value toward the creation of shared value for multiple stakeholders.

8.5 Education, capabilities and collaborative agenda

Research on education and capacity building should advance in several directions. This includes developing effective pedagogies to train professionals capable of systemic thinking and complexity management; creating serious games and simulations that allow experimentation with sustainability management in controlled environments where mistakes have no real-world consequences; and studying organizational learning processes and the dynamic capabilities needed to implement systemic sustainability. Together, these lines of work would help prepare the next generation of professionals and support the transformation of existing organizations.

This future research agenda is necessarily ambitious and goes beyond what any individual researcher or single project could address. However, it reflects the richness and complexity of the field of systemic sustainability. It underscores the need for collaborative, sustained efforts by a broad academic and practitioner community to advance knowledge and practice toward truly sustainable, resilient, and human-centric productive systems.

PART IV – FINAL REFLECTION

This doctoral dissertation has been developed at a historical turning point, when humanity is simultaneously facing a climate crisis, accelerated biodiversity loss, widening inequalities, and rapid technological disruptions that are reshaping how we live and work. In this context, sustainability cannot be just one corporate objective among many, or a secondary consideration subordinated to short-term economic growth. It must become the fundamental paradigm guiding the organization of productive and economic systems and, together with organizational agility, provide the basis for managing the growing complexity and uncertainty of contemporary supply chains.

Systemic sustainability, the integrative concept at the core of this research, seeks to respond to this urgency through approaches that are both academically rigorous and practically relevant. From this perspective, the sustainability of a productive system can be understood as its systemic health. Just as human health does not depend on a single organ or indicator but on the overall balance among systems and their relationship with the environment, the health of socio-technical systems depends on the balance among economic, environmental, social, and technological dimensions and on how these systems interact with their territories, communities, and ecosystems. Healthy systems are not defined by how far they can push their limits, but by how well they maintain long-term balance, regenerative capacity, and the ability to adapt without undermining that balance. Measuring and managing sustainability, therefore, means learning how to diagnose, monitor, and care for that systemic health over time, while ensuring that adaptive responses remain aligned with it.

The frameworks developed in this thesis are tools to support that task. The geoanthropological lens emphasizes territorial embeddedness and the inseparability of production, place, and community. The thermoeconomic perspective grounds sustainability in physical realities, highlighting that all economic activity is constrained by thermodynamic laws and by the quality of the resources it transforms. The data-driven SO-LCA approach operationalizes the social dimension, making visible impacts on stakeholders and communities that are often overlooked or treated only qualitatively. Together, these perspectives help move from an abstract notion of “sustainability” to a more concrete and measurable understanding of systemic health in industrial contexts, and show how agile reconfiguration of processes and relationships can, and should, take place within the boundaries set by that systemic health.

The transition toward Industry 5.0 and its projection toward Industry 6.0 is neither inevitable nor automatic. It will not occur simply because technology advances or markets evolve. It requires deliberate and sustained decisions, committed leadership at multiple levels, collaboration among diverse stakeholders, and political will to implement regulatory frameworks that steer transformations in socially desirable directions. It also requires overcoming deeply rooted institutional inertia, vested interests that benefit from the status quo, and cognitive frameworks that no longer fit contemporary realities but persist out of habit and lack of articulated alternatives. In this sense, agility, understood as the capacity to sense, learn, and reconfigure, becomes a necessary complement to systemic sustainability: without agility, sustainability remains rhetorical; without sustainability, agility degenerates into short-term opportunism.

Academic research can contribute to this transformation in several ways. It can offer visions of possible and desirable futures that expand our collective imagination of the alternatives that exist. It can develop concepts and theories that help us understand complex systems and anticipate the consequences of interventions. It can provide methodological tools that enable more sophisticated measurement, monitoring, and management of sustainability, systemic health, and adaptive capacity. It can also generate empirical evidence on what works, in which contexts, and why, reducing uncertainty around effective policies and practices.

However, academic research alone does not change reality. Real transformation requires collective action by multiple actors: firms that innovate business models and production systems, workers who renegotiate labor conditions and competencies, consumers who adjust consumption patterns, investors who redirect capital toward sustainable activities, communities that demand respect and participation, social movements that mobilize political pressure, and governments that design and enforce appropriate regulations. Coordination among these actors will always be imperfect, but it can still converge toward shared directions.

A central lesson of this dissertation is that such transformations cannot be addressed from within isolated theoretical frameworks. The complexity of systemic sustainability demands genuinely transdisciplinary approaches that cross and, when necessary, dissolve disciplinary boundaries. Geoanthropology, thermoeconomics, management sciences, life cycle assessment, and stakeholder analysis are not treated here as separate blocks, but as interconnected perspectives that must be integrated to understand and guide the health and adaptive behavior of socio-technical systems embedded in their territories. If this thesis has any distinctive feature, it is this attempt to inhabit the spaces in between disciplines, where many of today's most urgent questions reside.

This dissertation aspires to be a modest yet meaningful contribution to that broader process. If the frameworks and methodologies developed here find practical application in real organizations and help them manage sustainability more effectively and design agile responses consistent with it; if they inspire further research that extends and deepens the lines of inquiry initiated in this work; if they inform public policies that ease necessary transitions; and if they contribute, even marginally, to ensuring that organizational decisions give greater consideration to integral sustainability and justice, then the thesis will have fulfilled its fundamental purpose.

The path toward systemic sustainability is long and complex, and contradictions, setbacks, and detours will inevitably mark it. There is no linear route and no guarantee of success. Nonetheless, the endeavor is necessary because there is ultimately no realistic alternative. The sustainability of our productive systems is inseparable from the sustainability of our civilization and from the flourishing of present and future generations. The decisions we make, or fail to make, in the coming decades about how we organize production and consumption, how we distribute resources and opportunities, and how we balance economic efficiency with social equity and ecological stability will largely determine the kind of world that future generations inherit. This responsibility should generate urgency without leading to paralysis, inspire ambition without fostering naivety, and sustain a long-term commitment that recognizes how deep transformations require time, patience, and persistence.

In this context, systemic sustainability is not merely an academic construct but also an ethical and pragmatic imperative. It is ethical because it recognizes obligations toward other human beings, present and future, toward other species with whom we share the planet, and toward the ecosystems that sustain all life. It is pragmatic because unsustainable systems eventually degrade and may collapse, generating human, social, and economic costs that far exceed the investments required to prevent that degradation. The choice is not between sustainability and economic growth, but between a form of sustainability that enables continued prosperity and unsustainability that, sooner or later, leads to systemic failure.

This dissertation concludes with a cautious yet fundamental hope that the transformations required are possible. Historical experience shows that complex socio-technical systems can undergo profound change when actors clearly articulate alternative visions, broad coalitions mobilize effectively, and political windows of opportunity are used strategically. The energy transition from coal to oil and gas, the Green Revolution in agriculture, and the expansion of digital telecommunications, among many other transformations, demonstrate humanity's capacity to reorganize productive systems over relatively short periods when there is will, investment, and coordination. The transition toward systemic sustainability is more complex because it involves multiple dimensions and requires reconciling potentially conflicting objectives, but it is not impossible. Every step helps build this trajectory: every organization that adopts more sustainable practices, every policy that incentivizes transformation, every innovation that reduces impacts, and every shift in mindset that broadens our moral horizon contributes to a cumulative dynamic that may eventually reach tipping points at which systemic change accelerates.

If this research leaves any legacy, it will not lie in specific findings, which will inevitably be refined, questioned, and surpassed by future work. Its value will lie, if anywhere, in having contributed to articulating a vision of systemic sustainability as systemic health that is sufficiently comprehensive, rigorous, and operational to guide practical transformations. If that vision encourages other researchers, practitioners, policymakers, or students to keep working along these lines, and if it reinforces the conviction that healthier and more agile socio-technical systems are both necessary and possible, this thesis will have achieved its deeper purpose.

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