Sociotechnical or “socio-technical”? A Bibliometric Analysis of Conceptual Divergence in Innovation Research

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Abstract

As technology becomes increasingly intertwined with human activity, terminology must evolve to capture its complexity. This study investigates whether the terms “sociotechnical” and “socio-technical”—long assumed to be interchangeable—reflect distinct intellectual traditions. Through a bibliometric analysis of 9,254 records from the Web of Science (1994–2025), we identify a significant "Hyphen Gap." Our findings reveal a Maturity Paradox: while the hyphenated "socio-technical" was historically more consolidated, the unhyphenated "sociotechnical" has achieved a significantly higher degree of modern thematic synthesis (60.5% keyword convergence compared to 41.5% for the hyphenated corpus).

We demonstrate that the unhyphenated form acts as a broad, interdisciplinary boundary object bridging STS and system design, while the hyphenated form serves as a specialized disciplinary signal for the Multi-Level Perspective (MLP) and European-led policy transitions. We conclude that the choice of hyphenation is a strategic signal of epistemic alignment. Finally, we propose a new redefinition practice for conceptual development theory: Refining into a Continuum. This study provides the first systematic evidence that subtle linguistic variations encode deep intellectual divides, offering a "Strategic Map" for future interdisciplinary research.

Keywords: “sociotechnical”; “socio-technical”; Bibliometric; Maturity Paradox; Multi-level Perspective; Conceptual Divergence.

Jel Codes: O30; 031; 033

1. Introduction

For as long as *Homo sapiens* has existed, the species has been defined, in part, by the link between people and their tools. While this relationship is ancient, naming these hybrid forms remains a modern challenge. Historically, linguistic shifts have signaled deep conceptual changes; for instance, the term "cyborg" was coined by Clynes and Kline (1960) to describe human-machine adaptation, yet the concept was rooted in earlier responses to World War I prosthetics (Biro, 1994, 2009; Borck, 2005; Miller, 2018). Today, a similar but more subtle linguistic divergence is appearing within innovation research regarding the term "sociotechnical."

Originating in 1951 at the Tavistock Institute, the concept of the sociotechnical system (STS) was designed to describe the interdependence of social and technical dimensions in work environments (Trist & Bamforth, 1951). However, over the past seven decades, a hyphenated variant—"socio-technical"—has proliferated. While many scholars use these forms interchangeably, others have

begun to question whether the hyphen signals a stylistic preference or a substantive conceptual shift (Cooper & Foster, 1971; Klein, 2014; Ropohl, 1999; Sorrell, 2018). Interestingly, one of the original authors of the concept used both forms (Trist, 1978; Trist & Emery, 2015). This lack of clarity not only creates confusion in academic discourse but also has implications for practitioners who manage "sociotechnical" systems of various types.

The gradual bifurcation of these terms calls for a systematic appraisal. The presence or absence of a hyphen may indicate a deviation from the original intent of a synthesized, holistic system, suggesting instead a continuum where social and technical elements are viewed as separate subsystems. Despite their shared lineage, there is a significant gap in the literature regarding whether these terms have diverged into distinct disciplinary applications or epistemological frameworks. As a first step, a bibliometric study may help determine whether the two terms truly function as distinct concepts, which could justify deeper research into their respective uses (Daim & Yalcin, 2019; Gibson et al., 2018; Yalcin & Daim, 2021).

This paper addresses the following research question: Do the terms "sociotechnical" (without a hyphen) and "socio-technical" (with a hyphen) reflect distinct intellectual traditions? We approach this question through a bibliometric methodology and analyze more than 9,000 records published between 1994 and 2024 in the Web of Science Core Collection. Our study represents the first systematic, quantitative analysis of these terminological divergences and shows how subtle linguistic variations can correspond to distinct epistemological frameworks. The findings aim to clarify conceptual usage across domains, inform methodological alignment, and provide a foundation for future research on "sociotechnical" and "socio-technical" theory.

For our analysis, we employed the R programming language (R Core Team, 2024) and used the Bibliometrix package (Aria & Cuccurullo, 2017). This package has been used for insight (Bhatt et

al., 2021) and foresight (Naeini et al., 2022; Zamani et al., 2022). In our study, we use it to generate historical insights for the time period of 1994 to 2024. Our research offers a theoretical contribution by demonstrating that the term "socio-technical" is closely associated with the multi-level perspective (MLP) (Geels, 2005, 2019), whereas the term "sociotechnical" reflects broader application.

2. Literature Review

2.1. Origins and Theoretical Foundations

The term "sociotechnical" emerged in the early 1950s at the Tavistock Institute (Trist & Bamforth, 1951) to describe the interdependence of social and technical systems within organizational environments. This concept emphasized that neither the social nor the technical dimensions of work environments could be optimized in isolation. The approach influenced early systems thinking, particularly within industrial sociology and organizational development (Emery & Trist, 1965; Margherita & Braccini, 2021; Trist & Bamforth, 1951). The unhyphenated term "sociotechnical" originally represented a holistic and integrated framework in which social actors and technologies co-evolve within a single unified system.

Over time, the hyphenated variation "socio-technical" appeared in the literature. Although the terms are often used interchangeably, the introduction of the hyphen has raised questions about whether it signals a substantive conceptual shift or functions only as a stylistic artifact (Klein, 2014; Sorrell, 2018). Today, the two terms appear to anchor distinct intellectual and disciplinary traditions, which this paper examines systematically.

2.2. Disciplinary Divergence in Application

Subsequent literature within information systems extended the "sociotechnical" framework by examining how technology fits within complex social structures, particularly in organizational and digital contexts. Bostrom and Heinen (1977) presented a "socio-technical" perspective on management information systems and argued that many technological failures resulted from organizational misalignment. Trist (1978) reinforced the importance of jointly optimizing social and technical subsystems and positioned this as a design principle. Lewis Mumford (1983), the American philosopher of technology, expanded this tradition into participatory design and highlighted the importance of democratic values in workplace computing systems.

Baxter and Sommerville (2011) advanced the design of "socio-technical" systems and illustrated how engineering and social principles could integrate to create resilient systems. Their work was complemented by Cresswell and Sheikh (2013), who examined implementation failures in health information technology and found that many stemmed from poor alignment between social workflows and technical functionalities (Cresswell & Sheikh, 2013; Hacker & Binz, 2021; Jelavic, 2011). Within this literature, the "sociotechnical" label closely aligns with bottom-up design, user engagement, and the situated nature of knowledge work.

2.3. "Socio-technical" Framing in Policy and Thematic Synthesis

The hyphenated form "socio-technical" is prevalent in policy, sustainability, and governance literatures. Geels and Schot (2007) developed the MLP to conceptualize transitions as interactions across micro (niche), meso (regime), and macro (landscape) levels. This framework has since underpinned a wide range of empirical studies, including research on energy systems (Geels et al., 2018), urban transitions (Rutherford & Coutard, 2014), and transportation systems (Tuominen & Ahlqvist, 2010).

"Sociotechnical imaginaries," introduced by Jasanoff and Kim (2009), describe how national policy discourses are shaped by visions of technological futures that often mirror culturally embedded norms and power structures. These imaginaries play a central role in understanding the strategic framing of innovation and transitions. Similarly, Markard et al. (2012) and Smith et al. (2010) highlighted the importance of governance structures, actor coalitions, and institutional configurations in "socio-technical" transitions.

Current literature suggests that while the hyphenated form was historically more consolidated within European policy circles, the unhyphenated form may be achieving a higher degree of modern thematic synthesis across broader interdisciplinary boundaries. This study builds upon these observations to investigate whether subtle linguistic variations encode deep intellectual divides.

2.4. Research Gap: The Need for Systematic Differentiation

The terminological distinction between "sociotechnical" and "socio-technical" aligns with broader methodological and epistemological differences across scholarly domains. Studies that use the "sociotechnical" label often reflect qualitative, participatory, and interpretive paradigms. For example, Mumford (1983) emphasized the necessity of user involvement in system design, continuing a tradition rooted in the early work of Trist (1978) and Emery and Trist (Trist & Emery, 2015), which focused on workplace democracy and human-centered design. This stream of literature highlights the mutual shaping of human and technological systems from the bottom up, particularly within organizational and information systems contexts.

In contrast, research that adopts the "socio-technical" label is more prevalent in policy and sustainability transitions scholarship, where structured modeling frameworks dominate. Geels and Schot (2007), for instance, developed a typology of transition pathways grounded in the MLP. This

approach has been further extended in studies of national sustainability policy (Geels et al., 2016), governance of transitions (Smith et al., 2010), and the geography of sustainability transitions (Hansen & Coenen, 2015).

Methodologically, recent bibliometric contributions have provided empirical insights into the frameworks of these fields. Bhatt et al. (2021), Naeini et al. (2022), and Zamani et al. (2022) applied convergence analysis and science mapping techniques to detect conceptual clusters and thematic evolution across "socio-technical" topics. Their work shows that literature favoring the hyphenated form often concentrates on top-down systems thinking, whereas the non-hyphenated form commonly clusters around user agency and organizational change. This bifurcation reinforces our central hypothesis: subtle terminological variation encodes deeper intellectual, methodological, and disciplinary divides.

2.5. Comparative Summary: A Divided but Overlapping Terrain

In summary, although "sociotechnical" was originally conceived as a holistic framework that emphasizes the inseparability of social and technical systems, the hyphenated "socio-technical" has evolved in parallel and is often applied in contexts that require a more segmented analysis of subsystems. This divergence appears to be more than stylistic; it likely reflects deeper methodological and theoretical commitments. The "sociotechnical" literature generally employs interpretive, qualitative approaches rooted in organizational theory, as seen most recently in Iden and Bygstad (2025). In contrast, "socio-technical" is frequently situated within policy, engineering, and transitions research that benefits from formal modeling and structured frameworks such as the MLP as seen in Yang et al. (2025). Following this exploratory literature review, understanding how and why these two variants diverge—and whether they align with distinct scholarly communities—served as the central motivation for our subsequent bibliometric analysis.

3. Materials and Methods

3.1. Bibliometric Analysis

This research employs a bibliometric methodology to evaluate the conceptual and intellectual distinctions between the terms “sociotechnical” and “socio-technical.” Bibliometric methods provide a systematic means of identifying patterns in academic publications, including keyword usage, co-authorship, citation networks, and thematic clustering (Aria & Cuccurullo, 2017; Van Eck & Waltman, 2010; Bhatt et al., 2021). These methods are particularly useful for identifying conceptual divergence across disciplines, mapping scholarly communities, and uncovering emerging research trajectories (Gibson et al., 2018; Li et al., 2018).

All analyses took place in the R programming language (v4.3.3; R Core Team, 2024) using the Bibliometrix package (Aria & Cuccurullo, 2017). Bibliometrix is a well-established tool for science mapping and supports co-citation analysis, co-word analysis, conceptual structure mapping, and author collaboration analysis. To contextualize our approach, we drew on bibliometric analyses that explored multi-level sustainability transitions (Wang et al., 2022), disruptive innovation (Li et al., 2018), and societal megatrends (Jeflea et al., 2022). These studies illustrate how bibliometric tools can clarify concept migration and boundary definition across scholarly communities. Integration within the R environment enables full reproducibility, transparent coding of analytic steps, and flexibility when handling large datasets.

Our bibliometric strategy aimed to explore terminological distinctions based on co-occurrence, network patterns, and thematic clusters. We used standard Bibliometrix routines, including keyword normalization, co-word analysis of “keywords plus” (ID) and author keywords (DE), Multiple Correspondence Analysis (MCA, ultimately removed; see Results), and geographic authorship

mapping. This approach allowed us to compare the intellectual footprint of "sociotechnical" and "socio-technical" across multiple dimensions.

In April 2024, we collected data from the Web of Science Core Collection and focused on records that contained the terms "sociotechnical" and "socio-technical." The search covered two major indices: the Science Citation Index Expanded (SCI-EXPANDED) and the Social Sciences Citation Index (SSCI), across the period from January 1, 1994, to October 31, 2025. This search produced 5,014 records for "sociotechnical" and 6,271 records for "socio-technical," resulting in a comprehensive dataset for analysis.

The start date ensures coverage of early foundational articles such as Rip (1995). The cutoff date of October 31, 2025, reflects the acceptance timeline of the manuscript.

For data processing and analysis, we used the R programming language (Naeini et al., 2022) and the Bibliometrix package (Zamani et al., 2022), which is designed for bibliometric and scientometric analysis. All analyses were conducted using R Statistical Software (v4.3.3; R Core Team, 2024). Bibliometrix enabled detailed quantitative analyses of publication trends, keyword co-occurrences, and conceptual structures associated with each term. We cleaned and preprocessed the bibliographic data to ensure consistency and accuracy. This process included standardizing author keywords and Keywords Plus terms, removing duplicates, and normalizing variations in terminology. After this, we carried out co-word analysis, thematic mapping, and network analysis to identify patterns of usage and thematic relationships within the datasets. These steps supported a comparative evaluation of "sociotechnical" versus "socio-technical" terminological trends across the study period.

Our method draws on prior studies that used bibliometric approaches to differentiate conceptual spaces. For example, Li et al. (2018) analyzed the relationships between disruptive and emerging technologies, while Jeflea et al. (2022) mapped societal megatrends across four decades. Wang et al. (2022) also provided a useful precedent by examining how terms evolved differently within sustainability transition research through an MLP. Collectively, these studies offer both methodological and theoretical justification for the use of bibliometric tools in terminological analysis. Although bibliometric analysis offers robust quantitative insights, it cannot fully capture qualitative nuances such as context-specific interpretation or authors' intentions. However, given the extensive volume of literature and the increasing normalization of terminological variants, this approach remains appropriate for our goal of mapping divergence in scholarly usage. Future studies may complement our findings with discourse analysis or content analysis to better understand the semantic implications associated with each term. We provide the elements of our bibliometric analysis below.

3.2. Data collection and search criteria

Data were retrieved in late 2025 from the Web of Science Core Collection (SCI-EXPANDED and SSCI indices). We set the search period from January 1, 1994, to October 31, 2025, to ensure a comprehensive longitudinal view. This range includes "Early Access" and "Online-First" records that were indexed before their formal issue assignments in 2025. The final query produced two distinct datasets: 5,014 records for "sociotechnical" and 6,271 records for "socio-technical."

3.3. Analytical workflow

All processing and visualization were conducted in R (v4.3.3) using the Bibliometrix package (Aria & Cuccurullo, 2017). The workflow began with standardized preprocessing to unify author keywords (DE) and Keywords-Plus (ID), remove duplicates, and resolve orthographic variations.

To prioritize the intellectual core and eliminate peripheral noise, we subset the data to the top 500 most-cited articles for the primary network analyses.

To map the field's intellectual structure, we applied the Fruchterman-Reingold force-directed algorithm, ensuring that the spatial distance between nodes represents a direct, algorithmic measure of intellectual proximity. We utilized Louvain modularity-based clustering and PageRank centrality to identify core theoretical pillars within the reference co-citation networks. For the factorial thematic maps, we employed Walktrap community detection to calculate thematic density and keyword convergence. This strictly algorithmic approach allowed us to statistically measure epistemic drift and compare the structural maturity of the two terminological variants based on their normalized frequency divergence and network density.

The use of dual clustering algorithms—Louvain for reference networks and Walktrap for thematic maps—was intentional; while the Louvain method excels at identifying broad modular communities in large citation datasets, the Walktrap algorithm is better suited for the shorter-distance random walks required to define dense, high-resolution keyword clusters in factorial analysis.

4. Results

Our bibliometric analysis identifies two distinct intellectual traditions. While the terms are often used as synonyms, the data reveal significant divergence in theoretical associations and longitudinal growth. The unhyphenated "sociotechnical" shows broader interdisciplinary application, whereas the hyphenated "socio-technical" is statistically anchored to the Multi-Level Perspective (MLP).

4.1. Scientific production and relevant sources

The historical development of both terms (1994–2025) is illustrated in **Figure 1**. The total dataset comprises 9,254 records. Publication activity for both variants remained low during the 1990s,

243 rarely exceeding 20 publications per year. A primary inflection point occurred in 2007, followed by
244 a secondary, sharper acceleration after 2015. By 2020, annual production exceeded 400 articles,
245 peaking in 2023 with over 500 publications.

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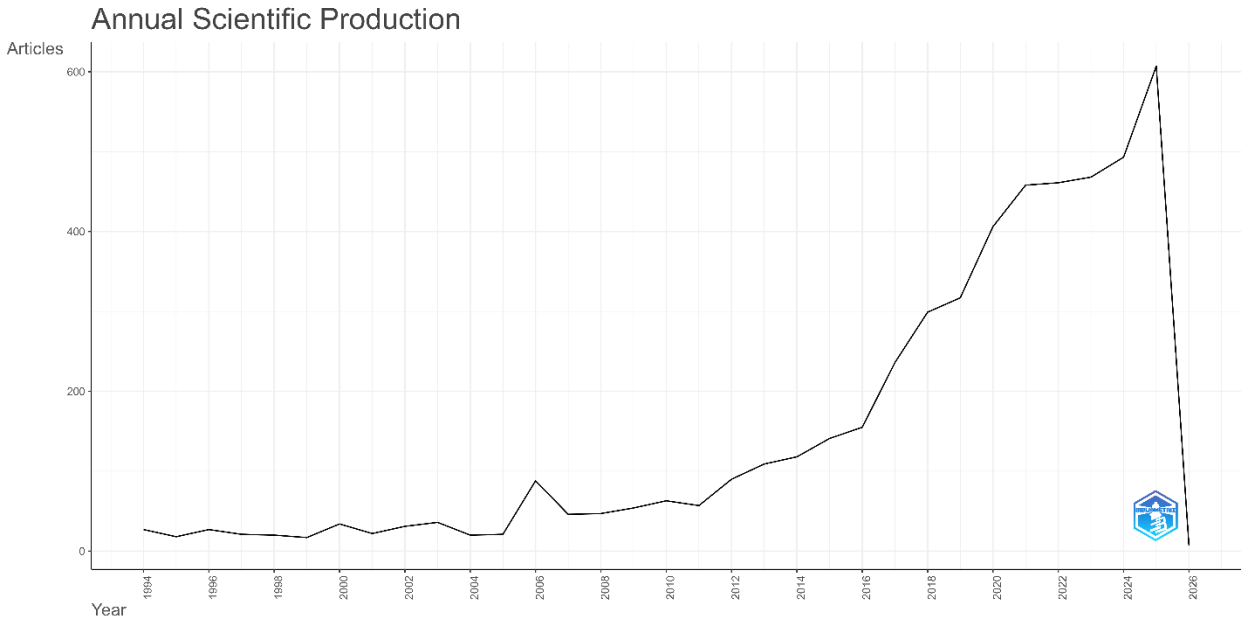

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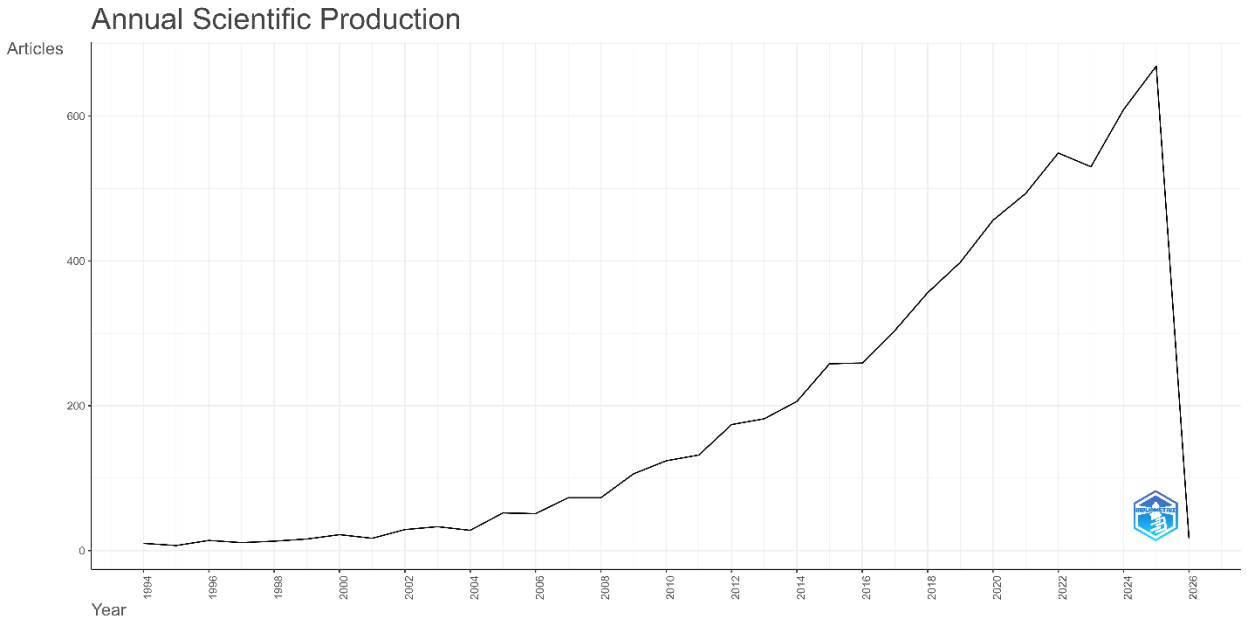

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Figure 1. Annual scientific production (1994–2025**). (a) Unhyphenated corpus; (b) Hyphenated corpus.**

4.2 Co-Citation Network Analysis

To investigate the intellectual foundations of the two terms, we conducted a co-citation analysis using the ForceAtlas2 spatialization algorithm. Modularity-based clustering (via the Louvain method) was applied to identify dominant intellectual traditions. The results demonstrate that while both corpora share foundational anchors, their underlying topologies reveal a significant "Hyphen Gap" in disciplinary orientation.

4.2.1 Series 1: Sociotechnical (Unhyphenated) Analysis

The co-citation network for the unhyphenated sociotechnical corpus (**Figure 2a**) reveals an integrated intellectual map (N=500) characterized by a pluralistic and interdisciplinary structure. With a modularity (Q) of 0.212, the network successfully bridges disparate fields through high-betweenness "bridge" nodes. Three distinct thematic pillars emerge:

- Sustainability Transitions (Red): Grounded in transition scholarship and sustainability regimes.
- STS/Imaginaries (Blue): Reflecting work on sociotechnical imaginaries and visions of scientific progress.
- Systems Engineering (Green): Linking the term to safety science and cognitive systems engineering.

As shown in the structural core (Figure 2b), the primary roles of Geels (2002), Jasanoff (2015), and Rasmussen (1997) as foundational anchors are clearly visualized. This multi-hub topology

confirms that the unhyphenated form functions as a flexible "boundary object," integrating organizational behavior with complex system design.

4.2.2. Series 2: Socio-technical (Hyphenated) Analysis

In contrast, the socio-technical co-citation network (see **Figure 2b**) exhibits extreme epistemic consolidation, evidenced by a low modularity ($Q < 0.10$) and higher density (0.192). This intellectual map reveals a "monolithic" architecture that lacks the distinct thematic branching seen in its unhyphenated counterpart.

The structural core reveals a network centered almost exclusively on the Multi-Level Perspective (MLP). At the center of this network, Geels (2002) emerges as the dominant reference in both citation frequency and connective density. Secondary nodes, such as Markard et al. (2012) and Kemp (1998), appear as direct extensions of this central hub rather than independent sub-communities. The lack of peripheral "bridge" authors confirms that the hyphenated form acts as a specialized disciplinary signal for the Sustainability Transitions community.

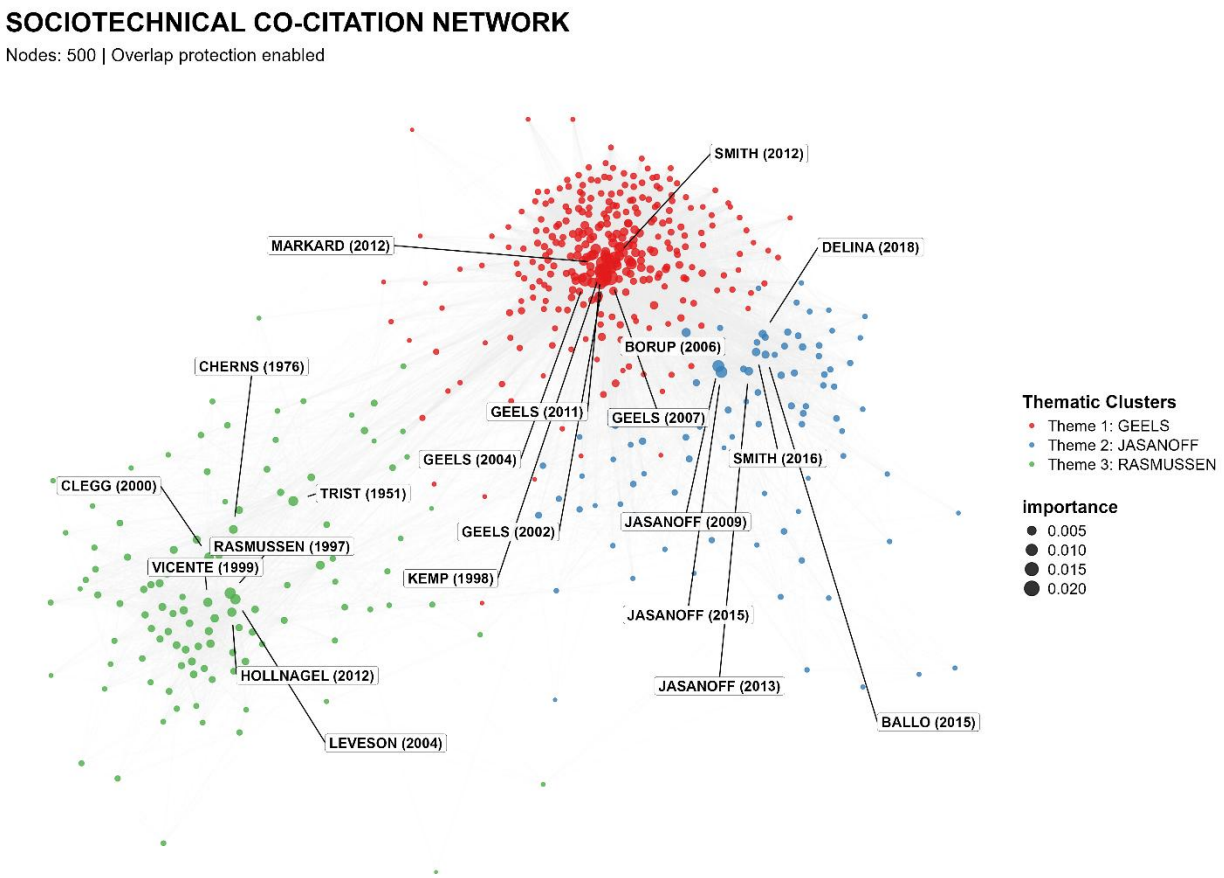
4.2.3. Comparative Insights

Despite sharing intellectual anchors such as Geels (2002) and Trist (1978), the two corpora diverge in their co-citation topologies, as illustrated in the comparison between Figure 2a and Figure 2b:

- Sociotechnical (Unhyphenated): Demonstrates greater epistemic diversity, spanning human factors, organizational design, and systemic safety. Its moderate modularity ($Q = 0.212$) reflects a well-structured network with distinct thematic branching and significant cross-cluster interaction.

- Socio-technical (Hyphenated): Reflects extreme disciplinary consolidation, centered almost exclusively on the MLP and governance-related transitions. Its low modularity ($Q < 0.10$) and higher density (0.192) reveal an architecture that lacks independent sub-communities.

These topological distinctions indicate that the unhyphenated and hyphenated forms represent separate, although overlapping, intellectual traditions. Each term encodes a different epistemological orientation: interdisciplinary pluralism for the unhyphenated form and epistemic consolidation for the hyphenated form.



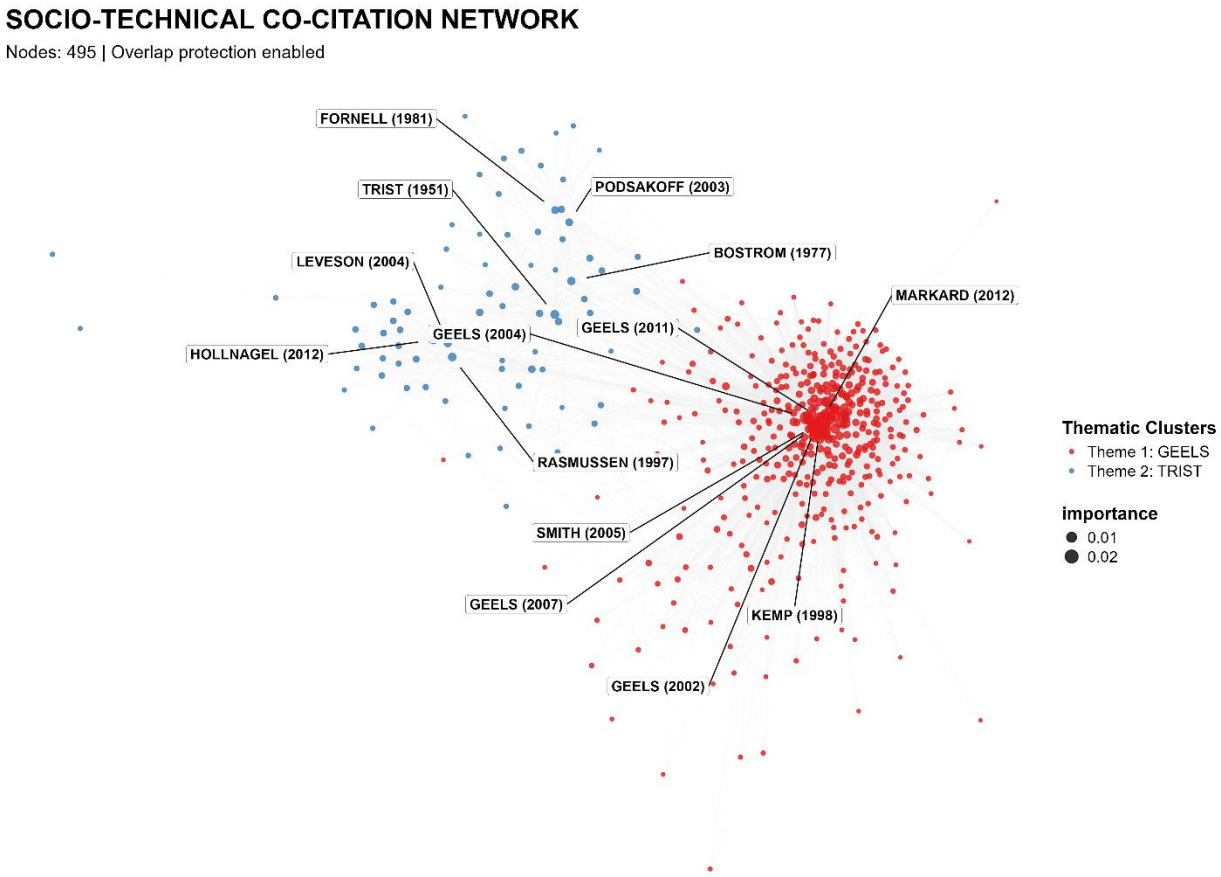


Figure 2. Reference Co-Citation Networks.

(a) Reference Co-Citation Network: Sociotechnical (Full Landscape). Integrated map (N=500). Node size proportional to PageRank centrality; edge thickness represents Link Strength. Identifies Red (Transitions), Blue (STS), and Green (Systems) pillars. Metrics: Density = 0.166; Modularity (Q) = 0.212; Avg. Path Length = 7.37.

(**b) Reference Co-Citation Network**: Socio-technical (Thematic Core). Convergent map showing extreme consolidation around a singular Sustainability Transitions hub. Metrics: Density = 0.192; Modularity (Q) < 0.10.

Note: To ensure the structural clarity of the bibliometric maps and prioritize the most significant data points, a frequency-based filtering threshold was applied to both the co-citation and co-occurrence networks. Specifically, the analysis was restricted to the top 500 most frequently cited references for the co-citation network and the top 500 most frequent keywords for the co-occurrence network using the bibliometrix R-package. Following the initial frequency filter, both networks were further pruned by removing weak ties (co-citation or co-occurrence weights less than or equal to 2 and isolated nodes to focus the analysis on the most robust thematic clusters.

4.3. The current research front: Keyword co-occurrence and divergence

Keyword co-occurrence identifies contemporary intellectual proximity based on the frequency with which specific terms appear together in the same articles. Our analysis reveals a "Maturity Paradox": while the hyphenated form was historically more consolidated around the Multi-Level Perspective (MLP), the unhyphenated "sociotechnical" has achieved a significantly higher degree of current thematic integration.

4.3.1. Divergence analysis: The "Difference Factor"

To identify the specific conceptual boundaries driving this maturity, we calculated the Normalized Frequency Divergence (Difference Factor) for shared keywords. This approach allows us to rank keywords by their relative bias toward one tradition over the other, rather than absolute frequency:

$$\text{Difference Factor} = \left| \frac{\text{Keyword}_{\text{Socio-Technical}}}{\text{Total}_{\text{Socio-Technical}}} - \frac{\text{Keyword}_{\text{Sociotechnical}}}{\text{Total}_{\text{Sociotechnical}}} \right|$$

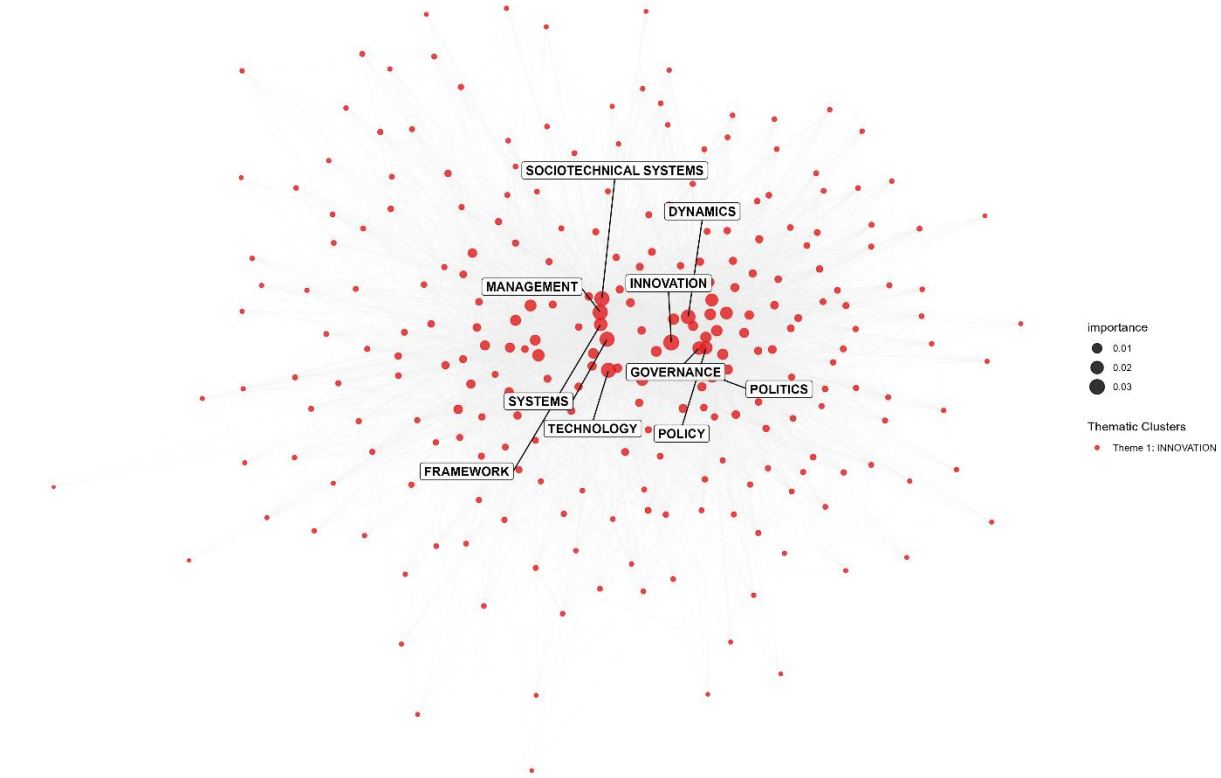
As shown in the keyword networks (see Figures 3a and 3b), the unhyphenated “sociotechnical” corpus is significantly more integrated, with a 3.2x higher normalized frequency for the specific term “sociotechnical systems.” It strongly dominates language rooted in Science and Technology

Studies (STS), such as “sociotechnical imaginaries,” “science,” and “design.” In contrast, the hyphenated “socio-technical” corpus exhibits structural sparsity and a higher relative bias toward institutional and macro-level language, including “governance,” “policy,” “framework,” and “sustainability.”

4.3.2. Thematic synthesis and maturity

The structural metrics confirm this divergence. The keyword co-occurrence network for the unhyphenated sociotechnical corpus (Figure 3a) demonstrates a remarkably mature and integrated scholarship. Utilizing the Louvain Method (Resolution 1.2), the network reveals dense inter-cluster connectivity, with 60.5% of the keywords converging on a sophisticated synthesis of innovation and sustainability transitions.

In contrast, the hyphenated socio-technical research front (Figure 3b) exhibits a more diffuse and exploratory structure. This network demonstrates significantly lower overall thematic density, with only 41.5% consolidation in recent work. The structural sparsity of the hyphenated network indicates that "socio-technical" is currently shifting toward newer, more isolated, or niche-specific domains that have yet to achieve the deep thematic overlap seen in the unhyphenated corpus.


SOCIOTECHNICAL KEYWORD CO-OCCURRENCE
Nodes: 250 | Clusters identifying core concepts
SOCIOTECHNICAL SYSTEMS
DYNAMICS
MANAGEMENT
INNOVATION
GOVERNANCE
POLITICS
SYSTEMS
TECHNOLOGY
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Thematic Clusters
Theme 1: INNOVATION

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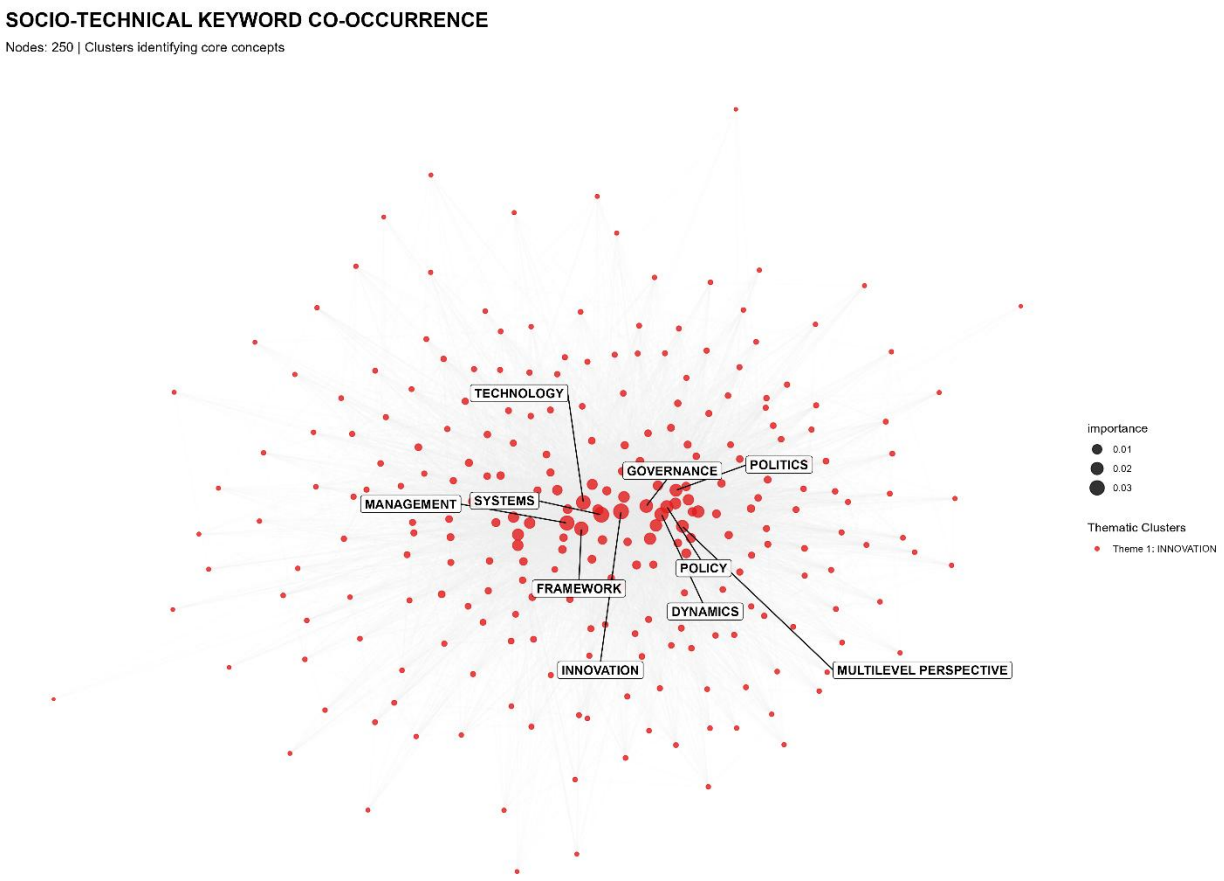


Figure 3. Keyword Co-occurrence & Divergence.

(a) Sociotechnical (Research Front). Dense thematic mapping (60.5% convergence). High "Difference Factor" for integrated terms like "sociotechnical systems" and "sociotechnical imaginaries."

(b) Socio-technical (Exploratory Phase). Sparse thematic mapping (41.5% convergence). High "Difference Factor" for institutional and policy-oriented terms like "governance," "policy," and "sustainability."

Note: To ensure the structural clarity of the bibliometric maps and prioritize the most significant data points, a frequency-based filtering threshold was applied to both the co-citation and co-

occurrence networks. Specifically, the analysis was restricted to the top 500 most frequently cited references for the co-citation network and the top 500 most frequent keywords for the co-occurrence network using the bibliometrix R-package. Following the initial frequency filter, both networks were further pruned by removing weak ties (co-citation or co-occurrence weights less than or equal to 2 and isolated nodes to focus the analysis on the most robust thematic clusters.

4.4. Geographic distribution and global influence

The geographical analysis of corresponding author countries (see Figure 4) provides a sociolinguistic lens through which to examine the "Hyphen Gap." By distinguishing between single-country publications (SCP) and multiple-country publications (MCP), we uncover distinct collaborative patterns that align with the conceptual framing of "sociotechnical" (unhyphenated) and "socio-technical" (hyphenated) research.

4.4.1. Collaborative dynamics: International vs. localized focus

The data reveals a substantial divergence in how these terms facilitate international collaboration. Research adopting the hyphenated "socio-technical" (Figure 4b) demonstrates a higher proportion of MCPs, particularly in the United Kingdom, the Netherlands, and Germany. This pattern suggests that the hyphenated form serves as a primary linguistic artifact for international research coalitions, likely due to its strong alignment with the Multi-level Perspective (MLP) and sustainability transitions scholarship prevalent in European policy circles (McGowan et al., 2020).

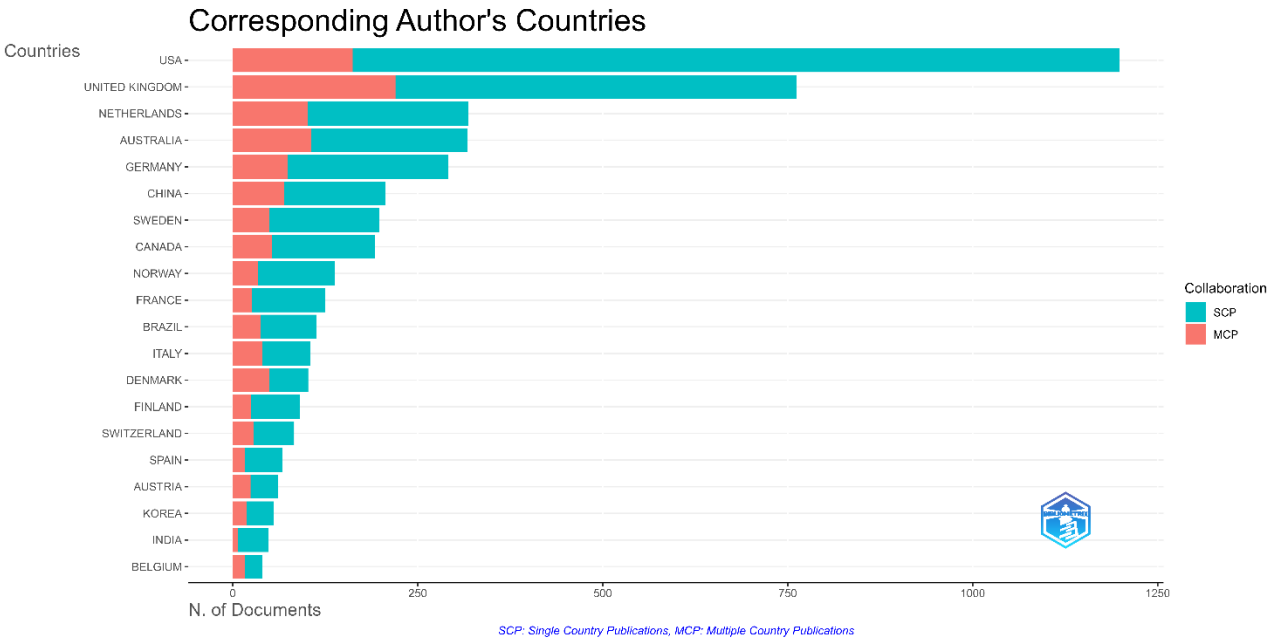
In contrast, the unhyphenated "sociotechnical" (Figure 4a) shows a higher frequency of SCPs, with a dominant concentration in the United States. This indicates a more localized, yet broader, application of the term that does not rely exclusively on the MLP framework. These findings

support our hypothesis of a transatlantic divide: the hyphenated form acts as a specialized disciplinary signal for European-led policy transitions, while the unhyphenated form maintains its role as a versatile, interdisciplinary boundary object in American scholarship.

4.4.2. Intellectual landscapes and global citation trends

The analysis of the most globally cited documents (**Figure 5**) further validates this divergence. For the unhyphenated "sociotechnical" corpus (Figure 5a), top-cited works—such as Geels and Schot (2007) and Pastor-Satorras et al. (2015)—span diverse domains including strategic management, innovation, and the social studies of science. This reflects the term's broad adoption as a flexible conceptual framework for exploring general technology–society interactions.

Conversely, the "socio-technical" literature is more concentrated within specific thematic boundaries. Highly cited documents in this corpus (Figure 5b) are frequently situated in policy-oriented and safety-focused journals (Carayon et al., 2006, 2011). The recurring dominance of Geels' work within this subset reinforces the hyphenated form's status as a label for structured analyses and specialized domains. This shift from the original Tavistock intent suggests that while "sociotechnical" continues to emphasize a unified system, "socio-technical" has evolved to facilitate the segmented analysis of social and technical subsystems within large-scale governance frameworks.



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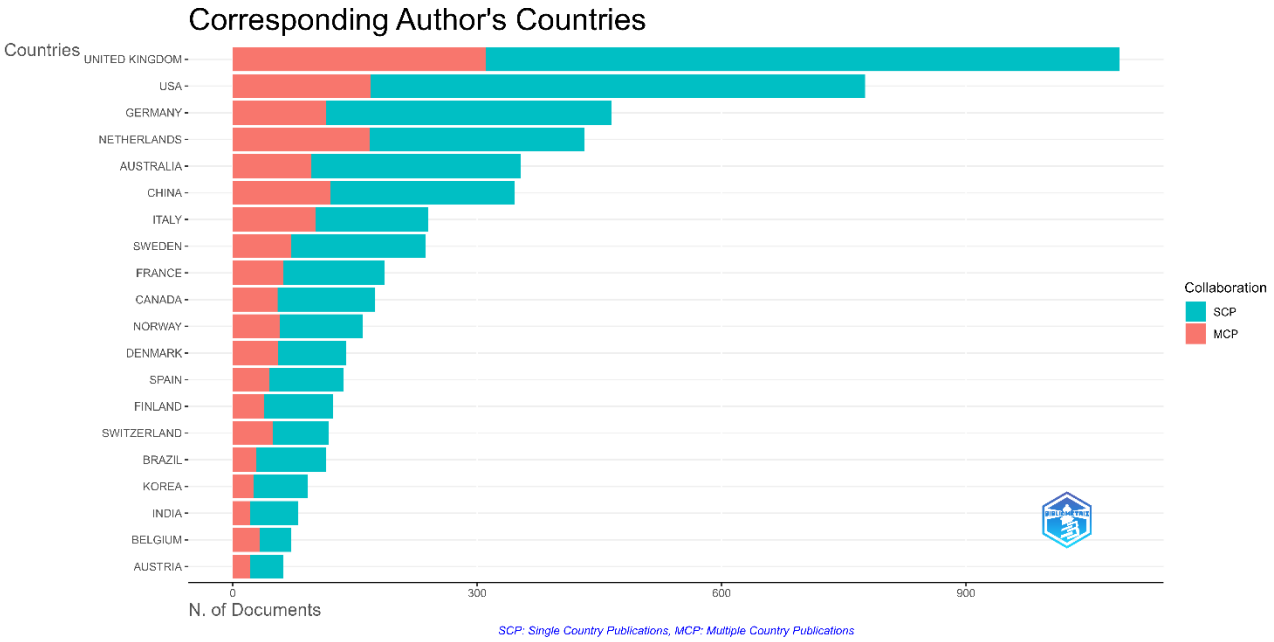

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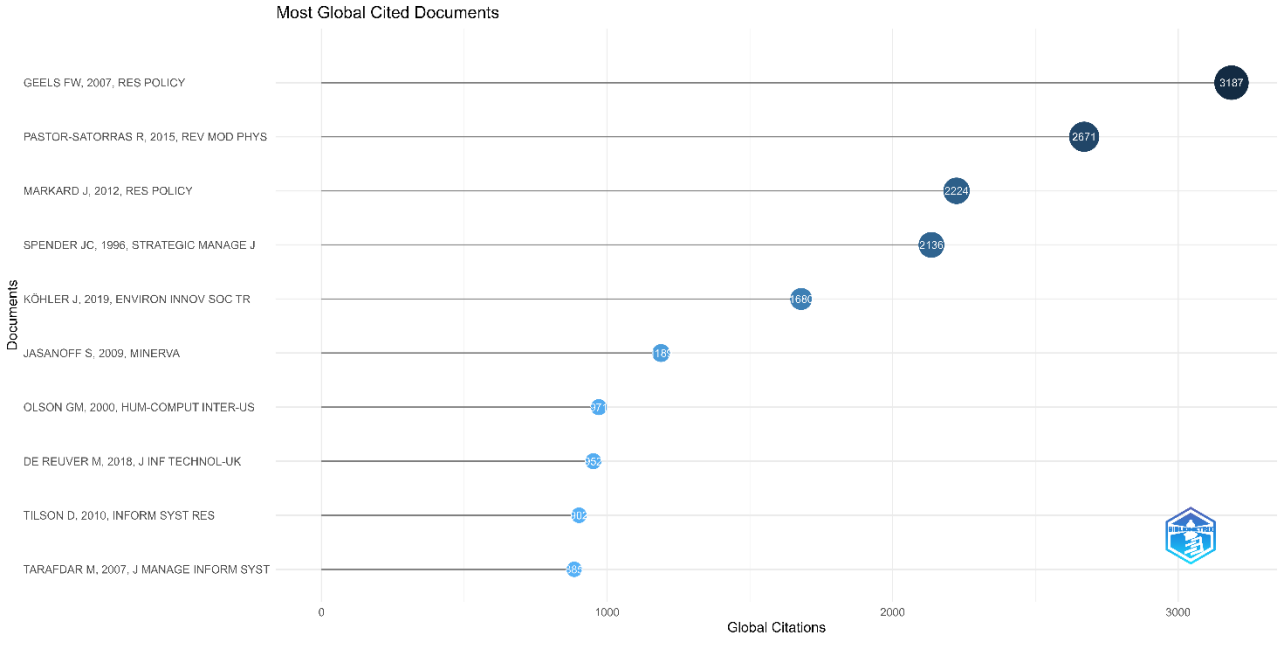
399 **Figure 4. Geographical distribution of corresponding authors.**

400 **(a) Sociotechnical (Unhyphenated).** Showing a high density of single-country publications (SCP)

401 and a strong presence in the United States.

(b) Socio-technical (Hyphenated). Characterized by a higher proportion of multiple-country publications (MCP) across European research hubs.



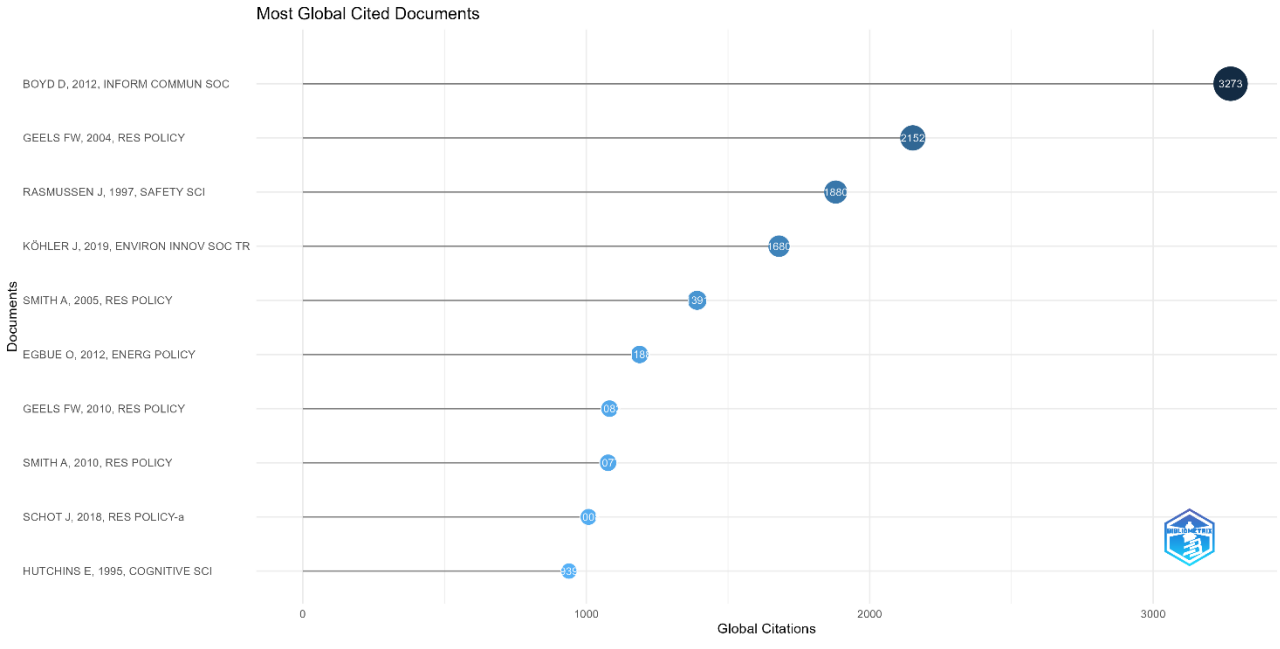


Figure 5. Top globally-cited documents.

(a) Sociotechnical (Unhyphenated). Foundational works driving the broad, interdisciplinary research stream.

(b) Socio-technical (Hyphenated). Influential documents driving the specialized, policy-oriented research stream.

4.5. Spatial Mapping: Factorial and Strategic Thematic Analysis

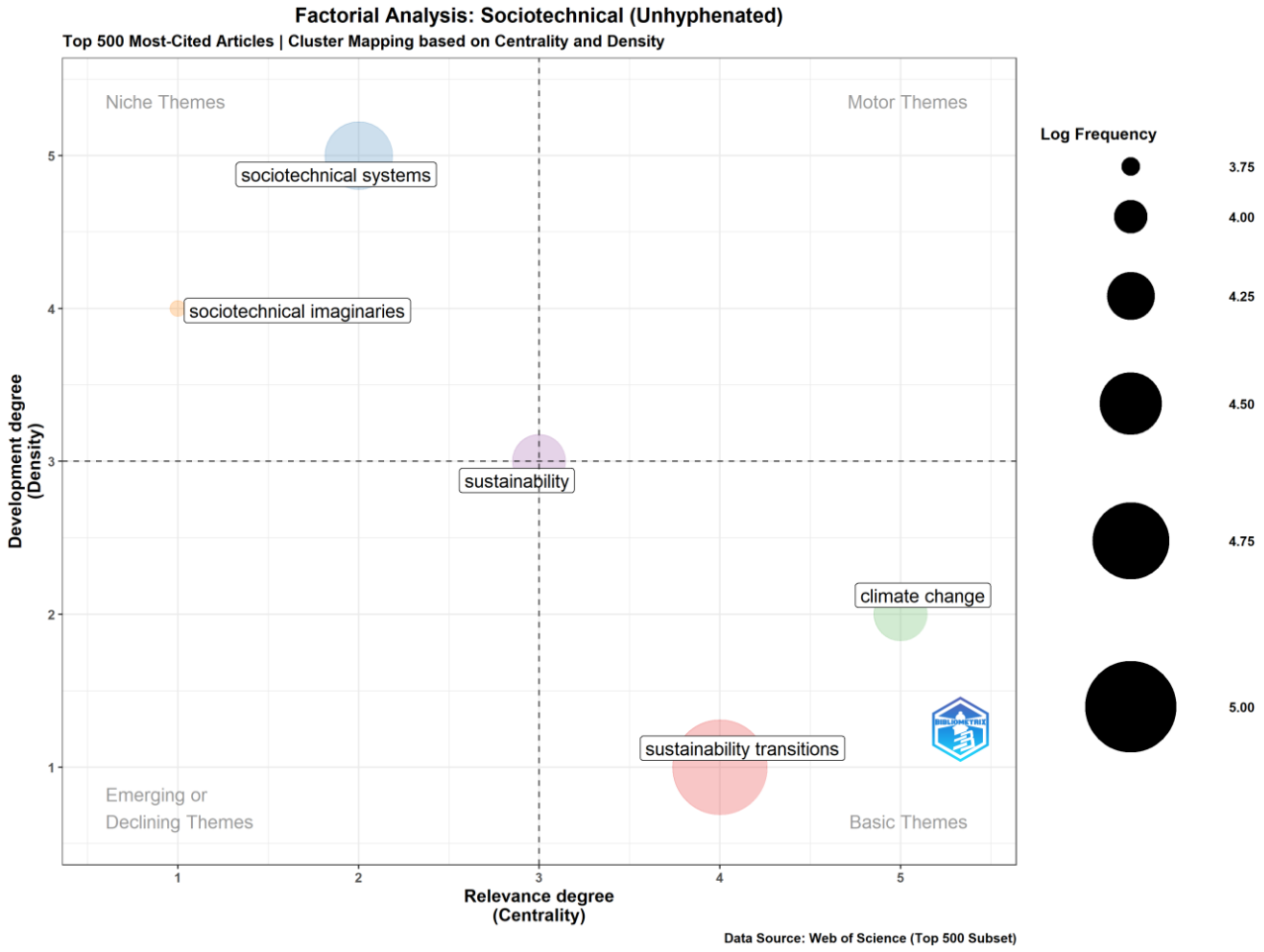
While the keyword networks (Section 4.3) identify the strength of direct co-occurrence, the factorial distribution—represented through strategic thematic mapping—visualizes the structural maturity and relational proximity of the intellectual landscape (see Figures 6a and 6b). By plotting keywords along dimensions of Centrality (Relevance) and Density (Development), this spatial mapping distinguishes between foundational concepts and specialized research fronts.

4.5.1. The "Umbrella" vs. the "Specialist"

The sociotechnical (unhyphenated) thematic map (Figure 6a) reveals a broad, dispersed conceptual landscape, confirming its role as an interdisciplinary umbrella concept. The mapping shows themes distributed across all four quadrants, from high-density niche applications to low-density emerging constructs. This configuration suggests that the unhyphenated form facilitates broad integration across diverse fields—ranging from "sociotechnical imaginaries" to organizational "implementation"—supporting its utility as a versatile boundary object for addressing complex systemic challenges.

In contrast, the socio-technical (hyphenated) map (Figure 6b) exhibits a more bounded and strategically concentrated clustering of terms. Key clusters such as "sustainability transitions,"

"multi-level perspective (MLP)," and "governance" appear with high centrality, indicating a strong alignment with systematic modeling and specialized policy research. The spatial configuration in Figure 6b confirms that the hyphenated term functions as a specialized disciplinary tool, primarily concentrated within the rigorous frameworks of environmental governance and energy transition studies.



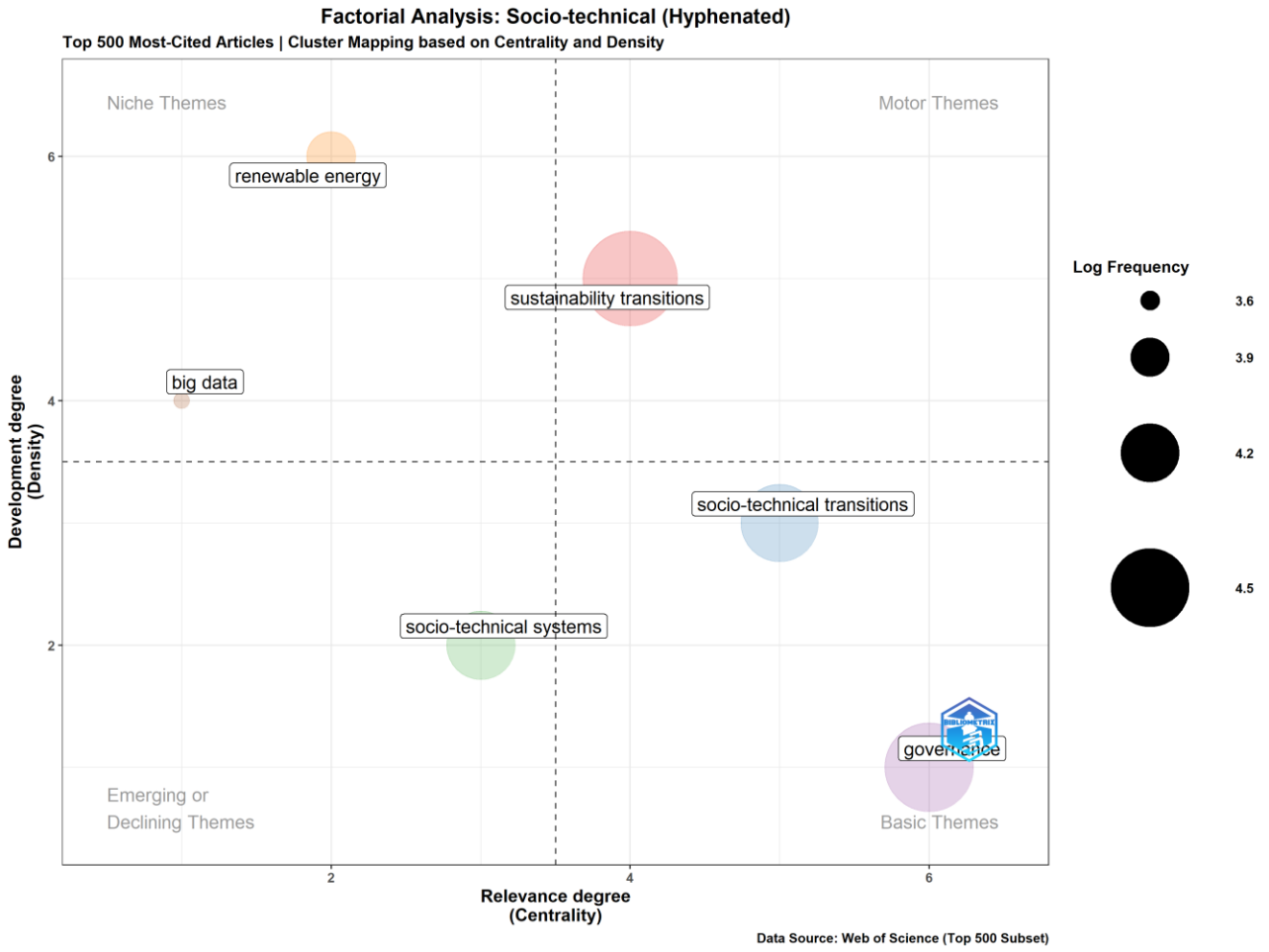


Figure 6. Factorial Analysis and Strategic Mapping of Keywords.

(a) Sociotechnical (Unhyphenated). Strategic map showing high conceptual dispersion, reflecting the term's role as a versatile, interdisciplinary umbrella concept supporting a wide array of emerging and foundational themes.

(b) Socio-technical (Hyphenated). Strategic map showing concentrated clustering around the MLP and transition frameworks, reflecting the term's role as a specialized disciplinary tool for policy-oriented research.

Note: To enhance structural clarity and mitigate computational noise associated with the full 5,000-record dataset, the factorial analysis was performed on a refined subset consisting of the top 500

most-cited articles. This approach prioritizes the intellectual core of the field while ensuring a robust signal for dimensionality reduction. Keywords were filtered using a frequency threshold (min. degree = 5) to focus on prominent thematic clusters. The resulting strategic diagram illustrates the relational position of themes in a two-dimensional space: the X-axis (Centrality) represents the external relevance of a theme to the entire field, while the Y-axis (Density) represents the internal development of the theme. Clusters are identified using the Walktrap community detection algorithm to isolate primary research fronts within the sociotechnical domain.

4.6. Comparative discussion: The "Hyphen Gap" and epistemic divergence

The collective structural metrics and thematic mappings across the sociotechnical (unhyphenated) and socio-technical (hyphenated) corpora confirm that the two terms are not interchangeable. Instead, they function as distinct disciplinary signals that encode different epistemological orientations.

4.6.1. Pluralism vs. specialization

The unhyphenated network serves as an interdisciplinary boundary object. Its moderate modularity (Q) and multi-hub topology (**Figure 2a**) allow it to bridge disparate fields—integrating the Tavistock tradition (Trist), Science and Technology Studies (Jasanoff), and Safety Science (Rasmussen). This "pluralistic" structure enables the term to remain a flexible tool for linking organizational behavior with complex system design.

In contrast, the hyphenated network exhibits extreme epistemic consolidation, functioning as a specialized instrument for the Sustainability Transitions community. Its high connectivity around a single central hub—Geels (2002)—and lack of distinct sub-communities (Figure 2b) suggest a

standardized and bounded vocabulary. Here, the hyphen acts as a "theoretical filter," focusing primarily on the Multi-Level Perspective (MLP).

4.6.2 Longitudinal dominance

The longitudinal growth metrics track the ascendancy of the transition paradigm. Both terms experienced a surge post-2010, but the unhyphenated "sociotechnical" has seen more rapid exponential acceleration. This suggests that as the field scales from individual workplaces to global climate systems, the unhyphenated form is being adopted as the preferred, more inclusive label for large-scale systemic analysis.

4.6.3. Detailed intellectual structure and top cited papers

When examining specific paper identity, the data further validates this "Hyphen Gap." The papers unique to the “sociotechnical” dataset focus on “sociotechnical imaginaries” (Jasanoff, 2009, 2015), whereas the top “socio-technical” papers address the MLP almost exclusively. This divergence is nearly absolute; when considering the papers within our dataset, significant overlap occurs only with Köhler et al. (2019) and Coenen et al. (2012).

4.6.4. Final synthesis: Implications for researchers

As synthesized in **Table 8**, the choice between "sociotechnical" and "socio-technical" is a strategic one. Researchers aiming for interdisciplinary breadth and the integration of classic systems theory should utilize the unhyphenated form. Conversely, those operating strictly within formal transitions and the MLP framework may find the hyphenated form more aligned with the established conventions of that specific epistemic community.

[Insert Table 8 about here]

4.7. Word clouds

Finally, we present the respective word clouds to visualize the foundational vocabulary of each corpus (**see Figure 7**). The sociotechnical (unhyphenated) cloud (**Figure 7a**) is visually dominated by terms such as "Technology," "Systems," "Innovation," and "Design." This hierarchy emphasizes the integration of these elements and reflects the term's holistic roots in the Tavistock Institute and systemic engineering.

In contrast, the socio-technical (hyphenated) cloud (**Figure 7b**) is dominated by "Systems," "Management," "Innovation," and "Governance." The central presence of "Governance" and "Policy" highlights the hyphenated form's role as a structural tool for state and institutional analysis, reinforcing its status as a specialized disciplinary signal for the sustainability transitions community.

500

501 **Figure 7.** Word cloud visualizations of foundational vocabulary.

502 **(a) "Sociotechnical" (Unhyphenated) Word Cloud.** Word frequency visualization showing a core

503 focus on integrated design, technology, and systems.

504 **(b) "Socio-Technical" (Hyphenated) Word Cloud.** Word frequency visualization showing a core

505 focus on governance, management, and institutional policy.

506 **5. Discussion**

507 This study set out to determine whether the terms *"sociotechnical"* and *"socio-technical"*—long

508 assumed to be interchangeable—actually reflect distinct intellectual traditions. Although the

509 existing literature discusses definitional ambiguity and conceptual breadth (Klein, 2014; Sorrell,

510 2018), it does not distinguish between the hyphenated and unhyphenated forms. Instead, both

511 spellings are typically treated as stylistic variants of the same foundational idea, originally

512 developed within the Tavistock tradition (Trist & Bamforth, 1951; Emery & Trist, 1965) and later

513 extended across organizational studies (Bostrom & Heinen, 1977), STS (Jasanoff & Kim, 2009;

514 Jasanoff, 2015), and sustainability transitions (Geels, 2005, 2019; Geels & Schot, 2007; Smith et

al., 2010). Our findings complicate this long-standing assumption. We demonstrate that these two spellings have evolved into empirically distinguishable research communities that maintain a tacit differentiation through divergent citation practices, keyword patterns, and collaborative networks.

5.1. Confronting existing scholarship with empirical findings

Previous scholars have argued that "sociotechnical" terminology suffers from conceptual looseness (Klein, 2014) or implied uniformity (Sorrell, 2018). Our results show that this presumption of uniformity masks a deep empirical bifurcation:

- The "Socio-technical" (Hyphenated) Corpus: This stream exhibits a highly consolidated structure centered almost exclusively on the Multi-Level Perspective (MLP). Dominant anchors include Geels (2002, 2011), Smith et al. (2010), and Markard et al. (2012). This confirms that the hyphenated term serves as a specialized marker of alignment with the sustainability transitions community.
- The "Sociotechnical" (Unhyphenated) Corpus: By contrast, this stream displays epistemic diversity, bridging STS, organizational design, human factors, and socio-material approaches. Works by Jasanoff (2015), Spender (1996), and Rasmussen (1997) hold structural centrality here but are largely absent from the hyphenated cluster.

Thus, the divergence we identify does not originate in explicit theoretical disputes but emerges organically through scholarly practice. This makes the distinction both consequential and previously invisible—an empirical insight not captured in earlier conceptual accounts.

5.2. Theoretical implications

Classical "sociotechnical" systems theory emphasizes joint optimization, participatory design, and "socio-technical" co-evolution (Cherns, 1976; Trist, 1978). The fragmentation observed in our findings indicates that this foundational integrative framework has splintered into multiple intellectual branches. The "sociotechnical" corpus retains these roots and extends toward organizational studies and STS. The "socio-technical" corpus, however, has largely detached from them. This divergence challenges the assumption, present in both organizational theory and transitions research, that a single unified "sociotechnical" lineage continues to exist.

Our results confirm the centrality of the MLP within the "socio-technical" corpus (Geels & Schot, 2007; Markard et al., 2012). They also show that its dominance is even stronger than most existing overviews describe. Nearly all top-cited "socio-technical" papers employ the MLP (Tables 3–5), whereas the "sociotechnical" corpus demonstrates a much more distributed conceptual base.

This raises important questions about epistemological narrowing within transitions studies, as well as whether conceptual consolidation around the MLP fosters theoretical maturity or restricts alternative approaches. Such alternatives include socio-ecological systems, complex systems models, and socio-material imaginaries (Hughes, 1987; Jasanoff, 2015; Köhler et al., 2018; Truffer et al., 2022).

The strong presence of "sociotechnical" imaginaries (Jasanoff & Kim, 2009; Jasanoff, 2015) in the unhyphenated corpus highlights continuing influence from STS. However, imaginaries are largely absent from "socio-technical" transitions research. This absence suggests a missed opportunity for integration. Transitions studies increasingly aim to incorporate governance, politics, and cultural meaning (Geels, 2016; Smith et al., 2010), yet they rarely engage directly with imaginaries despite their conceptual relevance.

The "Hyphen Gap" carries concrete risks for interdisciplinary collaboration. Misalignment occurs when one group assumes an MLP-based understanding of "socio-technical" systems while another works from a broader STS or participatory design perspective. Such disconnects can undermine policy design; for instance, a policy addressing a "socio-technical" system as a segmented model of subsystems may fail to capture the interpretive and cultural "imaginaries" central to an integrated "sociotechnical" analysis. As these frameworks become vital for AI governance and digital transformation, the ability to recognize these terminological distinctions is essential for conceptual coherence.

5.3. Future research and generalization: Refining into a Continuum

Future research can build on these findings in several directions. Temporal analyses could map when and how the divergence between “sociotechnical” and “socio-technical” emerged, particularly as transitions studies gained prominence after 2000. Qualitative content analysis of highly cited papers within each cluster would offer insight into whether the two terms differ semantically in practice or whether authors inadvertently signal methodological alignment through spelling choices. Additional work may examine geographic and linguistic patterns, given the uneven distribution of SCPs and MCPs across countries, to determine whether the divergence correlates with national research traditions or disciplinary training. There is also significant potential for theoretical integration. For example, future work may explore whether STS frameworks such as “sociotechnical” imaginaries can meaningfully combine with MLP-based transition models, or whether these perspectives rest on incompatible epistemological foundations. Finally, applying similar bibliometric approaches to other polysemous or contested concepts in innovation, STS, or organizational research may reveal broader patterns of linguistic drift and conceptual differentiation in interdisciplinary fields. Future research may also be directed towards determining whether and to

what extent the preceding findings hold across all time periods and publication venues, or whether it is concentrated in particular decades, journals, or disciplinary clusters.

Additionally, future research should conduct temporal analyses to map exactly when this "Hyphen Gap" emerged. There is also significant potential for theoretical integration: can STS frameworks like “sociotechnical imaginaries” meaningfully combine with MLP-based transition models, or do they rest on incompatible epistemological foundations?

Finally, we generalize our findings using the metatheoretical typology of Solinger et al. (2024). While they identify practices such as "theorizing" and "synthesizing," we argue that the trajectory of “sociotechnical” represents a new category: Refining into a Continuum. This constitutes a redefinition practice where subtle linguistic variants evolve to signal different degrees of systemic integration, allowing distinct epistemic communities to coexist while sharing a foundational vocabulary.

6. Conclusions

This study investigated whether the terms “sociotechnical” and “socio-technical” function as interchangeable descriptors or represent divergent intellectual traditions. Our bibliometric analysis, encompassing co-citation mapping, keyword co-occurrence, and factorial analysis, demonstrates that these two terms are not mere stylistic variants. Rather, they anchor distinct scholarly communities with different theoretical orientations, conceptual tools, and intellectual trajectories.

The “socio-technical” (hyphenated) corpus aligns narrowly with transition studies and the MLP framework, exhibiting a consolidated structure centered on sustainability, regime change, and innovation policy. In contrast, the “sociotechnical” (unhyphenated) corpus reflects broader epistemological traditions, drawing from STS, socio-materiality, and organizational theory. These

findings confirm that the choice of spelling is not trivial; it signals deeper ontological and methodological commitments.

While historical instances of hyphenation were likely stylistic, modern practice demonstrates a clear, if tacit, intentionality. The data confirms that the choice between "sociotechnical" and "socio-technical" is a strategic signal. The unhyphenated form has emerged as the preferred vehicle for interdisciplinary synthesis and mature, large-scale systemic analysis (60.5% convergence). The hyphenated form, while foundational to transition studies, now functions as a label for specialized or exploratory research within the transitions framework.

As with all bibliometric analyses, several limitations apply. Reliance on the Web of Science Core Collection may underrepresent books or non-indexed journals. Furthermore, corpus construction based on terminology may misclassify some articles, and clustering outcomes remain sensitive to algorithmic parameters. While citation patterns cannot fully capture every semantic nuance, these limitations do not undermine the robustness of the observed structural differences between the two corpora.

Taken together, the results underscore a broader implication: linguistic variants matter not merely as stylistic choices but as signals of epistemic alignment and intellectual lineage. By making these distinctions visible, this study contributes to greater conceptual clarity and reflexivity in interdisciplinary research, while also offering tools that future scholars may apply to other evolving concepts across the social sciences.

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Table 1. Keywords with the greatest frequency difference.

Keyword	Socio-technical	Sociotechnical
SOCIOTECHNICAL SYSTEMS	120	386

SYSTEMS	585	408
SOCIOTECHNICAL TRANSITIONS	50	170
FRAMEWORK	423	290
MANAGEMENT	530	397
TRANSITIONS	292	179
SUSTAINABILITY	275	167
PERFORMANCE	287	181
INNOVATION	522	405
SOCIOTECHNICAL IMAGINARIES	14	89
CHALLENGES	197	113
PERSPECTIVE	224	141

POLICY	331	243
ENERGY	258	175
IMPACT	261	178

862 Table 2. Most frequently cited papers: “Sociotechnical” (External Citations).

Rank	Paper	Citations	Subject/Contribution
1	Geels (2002)	536	MLP on technological transitions
2	Geels & Schot (2007)	493	MLP on transition pathways
3	Geels (2004)	389	Institutional theory and the MLP
4	Jasanoff (2015)	330	Sociotechnical imaginaries and public purpose
5	Jasanoff & Kim (2009)	282	Science, technology, and political power
6	Markard et al. (2012)	282	Sustainability transitions research fields
7	Geels (2011)	271	MLP on sustainability transitions

8	Kemp et al. (1998)	252	Strategic niche management
9	Smith (2005)	230	Evolutionary application of the MLP
10	Smith (2012)	225	Role of niches in the MLP

863

864 Table 3. Most frequently cited papers for "Socio-technical."

	Paper	Citations	Subject
1	Geels (2002)	733	MLP on technological transitions
2	Geels & Schot (2007)	609	MLP on "sociotechnical" transition pathways
3	Geels (2004)	453	Applies sociology, institutional theory, and innovation theory to the MLP
4	Markard et al. (2012)	383	Identifies major research fields and dynamics in sustainability transitions
5	Geels (2011)	332	MLP on sustainability transitions

6	Kemp et al. (1998)	327	Introduced strategic niche management, or how to expedite a transition into a new regime, which comprise the lowest level of the MLP
7	Smith et al. (2005)	294	A quasi-evolutionary application of the MLP in which niches continuously face selection pressure
8	Smith and Raven (2012)	250	Develops the role of niches in the MLP
9	Köhler et al. (2019)	241	An agenda for sustainability transitions research, including the MLP
10	Schot & Geels (2008)	235	Summarizes 10 years of strategic niche management research

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866

867 Table 4. Most frequently cited papers for "Sociotechnical" considering only the papers in the
868 dataset.

	Paper	Citations	Subject
1	Geels & Schot (2007)	493	MLP on "sociotechnical" transition pathways
2	Jasanoff & Kim (2009)	330	Uses "sociotechnical" imaginaries to address the relationship between science, technology, and political power, which is putatively undertheorized
3	Markard et al. (2012)	282	Identifies major research fields and dynamics in sustainability transitions
4	Köhler et al. (2019)	215	An agenda for sustainability transitions research, including the MLP
5	Coenen et al. (2012)	129	Acknowledging the specific geographical contexts of sustainability "sociotechnical" transitions in the MLP
6	Jasanoff & Kim (2013)	104	Explores how "sociotechnical" imaginaries (collective visions

			of how a society should be structured around a specific technology) influence national energy policies
7	Markard & Truffer (2008)	101	Compares and contrasts technological innovation systems and the MLP
8	Hansen & Coenen (2015)	96	Literature review on the geography of sustainability transitions
9	Clegg (2000)	94	A revised set of "sociotechnical" principles to guide system design
10	Geels et al. (2017)	91	A "sociotechnical" framework to accelerate innovation for deep decarbonization in the MLP

869

870 Table 5. Most frequently cited papers for "Socio-technical" considering only the papers in the
871 dataset.

	Paper	Citations	Subject

1	Geels (2004)	453	Applies sociology, institutional theory, and innovation theory to the MLP
2	Smith et al. (2005)	294	A quasi-evolutionary application of the MLP in which niches continuously face selection pressure
3	Köhler et al. (2019)	241	An agenda for sustainability transitions research, stating that transition studies essentially consist of Technological Innovation System, MLP, Strategic Niche Management, and Transition Management
4	Smith et al. (2010)	234	Applies the MLP to innovation studies for sustainable development
5	Geels (2010)	215	Demonstrates the MLP as a middle-range theory that makes crossovers to some ontologies and not to others
6	Geels et al. (2016)	168	Reformulates the MLP transition pathways typology through the lens of enactment
7	Geels (2012)	145	Applies the MLP to transport studies
8	Coenen et al. (2012)	144	Acknowledging the specific geographical contexts of sustainability "sociotechnical" transitions in the MLP
9	Geels (2005)	143	Applies the MLP to the horse-to-automobile transition in 1860–1930 USA.

10	Fuenfschilling & Truffer (2014)	141	Applies institutional theory to "sociotechnical" regimes in the MLP

872

873 Table 6. Top manuscripts per citation for "Sociotechnical."

	Paper	TC	TCperYear	NTC
1	Geels (2007)	3187	167.7	21.09
2	Pastor-Satorras et al. (2015)	2671	242.8	33.60
4	Markard et al. (2012)	2224	158.9	28.87
3	Spender (1996)	2136	71.2	18.94
5	Köhler et al. (2019)	1680	240.0	38.62
6	Jasanoff & Kim (2009)	1189	69.9	14.94
7	Olson & Olson (2000)	971	37.3	10.12
8	De Reuver et al. (2018)	952	119.0	17.99
9	Tilson et al. (2010)	902	56.4	13.00
10	Tarafdar et al. (2007)	885	46.6	5.86

874

875 Table 7. Top manuscripts per citation for "Socio-technical."

	Paper	TC	TCperYear	NTC
1	Boyd & Crawford (2012)	3,273	233.8	36.81
2	Geels (2004)	2,152	97.8	18.92

3	RASMUSSEN J, 1997, SAFETY SCI	1,880	64.8	8.19
4	Köhler et al. (2019)	1,680	240.0	34.69
5	Smith et al. (2005)	1,391	66.2	19.14
6	Egbue & Long (2012)	1,188	84.9	13.36
7	Geels (2010)	1,082	67.6	11.65
8	Smith et al. (2010)	1,077	67.3	11.59
9	Schot & Steinmuller (2018)	1,008	126.0	20.49
10	Hutchins (1995)	939	30.3	5.76

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877 Table 8. Summary of key findings: The Sociotechnical vs. Socio-technical divergence.

Metric	Sociotechnical (Unhyphenated)	Socio-technical (Hyphenated)
Epistemic Identity	Interdisciplinary Boundary Object	Specialized Disciplinary Label
Network Topology	Pluralistic & Multi-Hub	Convergent & Monolithic
Modularity (Q)	Moderate (0.212)	Low (< 0.10)
Primary Framework	Hybrid Integration (Tavistock/STS)	Theoretical Consolidation (MLP)
Research Front	Mature & Integrated (60.5%)	Diffuse & Exploratory (41.5%)

Growth Trajectory	Exponential Acceleration	Steady Specialization

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