Proc. of the European Safety and Reliability Conference (ESREL 2026)
Edited by José C. Matos, Paulo B. Lourenço, Michael Beer, Daniel Oliveira, Edoardo Patelli, Hélder S. Sousa, Rui A. Silva and Monica Santamaria
 Published by Research Publishing, Singapore.
doi: 10.3850/ESREL2026061419_esrel26-p27703-cd

The unspoken theory: How 'socio-technical systems' are used without being theorized in safety research

Aud M. Wahl

Department of Industrial Economics and Technology Management, Norwegian University of Science and Technology, Norway. E-mail: aud.wahl@ntnu.no

Hanne Finnestrand

Department of Industrial Economics and Technology Management, Norwegian University of Science and Technology, Norway. E-mail: hanne.finnestrand@ntnu.no

Socio-technical thinking is widely used in safety science, yet the concept of 'socio-technical systems' is applied in diverse and often inconsistent ways. Rather than reflecting a shared theoretical foundation, the term frequently serves as a broad label for different system perspectives, with substantial variation in how its core ideas are understood and operationalized. This literature review examines how the term is currently interpreted in recent safety research and discusses the implications of this diversity for theory and practice in complex work settings. The review shows that while some studies explicitly build on the classical socio-technical systems tradition of the Tavistock Institute, emphasizing principles such as joint optimization, autonomy, and participation, others use the term more loosely, drawing mainly on neighboring fields such as human factors, resilience engineering, or risk management. These patterns reveal differing assumptions about what constitutes a socio-technical system, ranging from structured, model-based views to more adaptive, practice-oriented understandings. The paper argues for greater theoretical clarity in the use of socio-technical concepts in safety science. Without such reflection, there is a risk of conceptual dilution and missed opportunities to build on the distinctive contributions of the classical socio-technical systems tradition in addressing contemporary safety challenges.

Keywords: Socio-technical systems, Safety science, Human factors

1. Introduction

Socio-technical thinking has gained prominence in safety science for its emphasis on complexity, interdependence, and multi-level system interactions. It frames safety not as the outcome of isolated human or technical failures, but as an emergent property of dynamic interactions among people, technologies, and organizational structures. Despite its growing popularity, the term 'socio-technical systems' is often used without reference to its theoretical foundations and as shorthand for complexity, rather than as a coherent analytical perspective (Waterson et al., 2015; Polojärvi et al., 2023). This tendency risks weakening its conceptual clarity and practical relevance.

Socio-technical systems (STS) theory originated from the postwar work at the Tavistock Institute (Trist & Bamforth, 1951). It was developed in response to the unintended effects of mechanization in British industry, focusing on the joint optimization of social and technical subsystems. The theory challenges the assumptions of technological determinism by demonstrating that safety, productivity, and job satisfaction improve when new technologies are introduced in ways that preserve worker autonomy, team integrity, and meaningful participation (Trist, 1981).

Today, the need for a theoretically grounded socio-technical perspective is more urgent than ever. Rapid digitalization, the integration of AI in operational decision-making, and the spread of autonomous and distributed systems are transforming how work processes are managed and experienced. These changes create new dependencies and shift control in ways that increase systemic complexity, precisely the kinds of conditions STS theory was developed to address (Wulff & Finnestrand, 2023). This is supported by Patriarca et al. (2021), who explain how socio-technical systems now include interconnected cyber-technical artifacts and can be described as cyber-social-technical systems. They argue that the safe operation of these systems depends on the operators' ability to adapt.

Against this backdrop, it becomes crucial to examine how STS theory is currently understood and applied. Without a shared understanding of its theoretical premises and methodological implications, it may become too vague to guide research or practice effectively. This article conducts a scoping review of recent literature to examine the following research question: *How is socio-technical systems understood and applied in safety science literature, and what are the practical implications of these interpretations for safety in complex work environments*?

2. Systems thinking

To understand how the term 'socio-technical systems' is understood and applied in safety science, it is essential to examine the theoretical foundations that inform this perspective. Systems theory emerged in the early twentieth century in response to the limitations of analytic reduction and the need to better understand the complexity of evolving systems (Carayon et al., 2015; Waterson et al., 2015; Read et al., 2017). It is a broad term for theoretical frameworks that study complex systems in nature, society, and science, for example, the general theory of adaptive systems in cybernetics (Ashby, 1956).

Systems theory is not a single, unified theory. Instead, it is a way to conceptualize an organization's structure and properties by emphasizing relationships and interdependence among its components. It focuses on interactions within systems, aiming to understand how they function theoretically.

The term 'systems thinking' derives from this perspective and typically denotes the application of the same principles in a practical, problem-solving manner (Read et al., 2017). It emphasizes the importance of viewing the big picture, recognizing patterns, and understanding the interconnections between various components of a system. A significant contribution to systems thinking is the development of socio-technical systems (STS) theory.

2.1. *The Tavistock tradition*

STS theory emerged after World War II at the Tavistock Institute of Human Relations in the United Kingdom, drawing on group psychology, applied social science, and action research traditions influenced by Kurt Lewin (1946). Early researchers sought to understand how work systems could be designed to better integrate human and technical elements (Trist, 1981).

A formative moment was the well-known study of British coal mines, where Trist and Bamforth compared traditional team-based mining with newly introduced mechanized systems. While mechanization aimed to increase efficiency, it fragmented work and reduced miners' autonomy, resulting in lower safety, weaker motivation, and higher absenteeism. In contrast, self-managing teams responsible for integrated sets of tasks achieved better performance and stronger commitment (Trist & Bamforth, 1951). These findings established the core STS principle of joint optimization—the idea that social and technical systems must be designed together.

Joint optimization holds that performance depends not only on advanced technology but on how technology supports human judgment, collaboration, and learning. Instead of narrowly specialized jobs, STS promotes the design of whole work systems organized around autonomous teams that manage interdependent tasks and take collective responsibility for outcomes. A key concept is redundancy of functions (Emery, 1967), which emphasizes multiskilling and overlapping competencies rather than strict specialization, enabling flexibility in complex environments. In this perspective, people are not treated as extensions of machines, but as active contributors who shape and complement technological systems.

2.2. *Human-centered design*

Building on these design principles, STS frames work systems as open systems embedded in dynamic environments. Influenced by Emery and Trist (1965), this perspective treats variation not as a problem to be eliminated but as an inherent condition of real work. To remain viable, organizations must therefore increase their internal capacity for adaptation rather than rely on rigid control. Emery further conceptualized socio-technical systems as purposeful, learning-oriented entities, shaped by human agency, values, and intentions rather than by technical structures alone (Emery, 1967). This shifts the focus of system design from command and control toward autonomy, participation, and development (Emery & Emery, 1974).

These ideas have direct implications for managing technological and organizational change. Research shows that performance improves when employees actively participate in shaping both the design and ongoing development of their work systems (Pasmore et al., 2019). Those closest to daily practice often hold critical knowledge about how technologies actually function and how they can be improved in use. In this respect, STS aligns closely with participatory design and action research, where involvement of those affected by change is seen as both a democratic principle and a practical requirement for sustainable performance (Pasmore, 2001). As Pasmore et al. (2019) argue, such participatory processes can generate “win-win-win-win” outcomes: stronger commitment, more effective technology use, improved organizational performance, and greater adaptive capacity.

3. Method: Scoping review

This article examines how the term socio-technical systems is used in recent safety science literature and discusses the implications of prevailing interpretations for safety research in complex work environments. To map how the concept is applied across studies, we conducted a scoping review, a method suited to exploring the breadth and characteristics of a research field rather than evaluating study quality (Arksey & O’Malley, 2005).

Scoping reviews are particularly useful for identifying patterns in how concepts are used, highlighting research gaps, and informing future, more systematic reviews (Parè et al., 2015). This approach therefore aligns well with the aims of the present study.

The review followed the five-stage framework proposed by Arksey and O’Malley (2005): identifying the research question, locating relevant studies, selecting studies, synthesizing and interpreting the data, and reporting the results.

We used the following search string: *((safety OR risk) AND ("sociotechnical system*"))*. We were aware that the term 'socio-technical systems' is widely used across fields and may lead to numerous inappropriate references. Since our goal was to get an indication of the range and nature of studies that include the STS perspective, we limited the search to Scopus, which is a comprehensive and trusted database for ‘safety science literature’.

3.1. *The selection process*

The search was limited to English-language, peer-reviewed literature published in 2016-2025. Irrelevant subject areas such as mathematics, physics and astronomy, genetics and molecular biology, chemistry, neuroscience and pharmacology, toxicology, and pharmaceutics were excluded. The search was conducted in February 2025. This process identified 319 studies. The abstracts of all these studies were uploaded to the software tool ‘Rayyan’ (https://www.rayyan.ai/) for further scrutiny.

The software identified six possible duplicates, prompting the removal of two articles before proceeding. The titles, keywords, and abstracts of the remaining 317 articles were read and categorized either as ‘include’, ‘exclude’, or ‘maybe’. A total of 150 articles were excluded during this process; many were not related to safety science, for example, several addressed economic risk. This initial review also made it evident that many articles use the term ‘socio-technical system’ as a substantive to denote a research context rather than a theoretical perspective, for example, in studies of complex socio-technical systems such as power plants, aviation, or the oil and gas industry. Many of these were placed in the ‘maybe’ category. The second screening led to a more detailed examination of these 81 articles, and 52 were subsequently excluded. The third screening reviewed the remaining 115 articles, including the introduction, theoretical framework, and conclusion. 52 articles were excluded, and the 44 that remained were scrutinized in greater detail. These processes identified 21 articles that were deemed relevant to our study.

These articles were synthesized and interpreted using the charting technique described by Arksey & O’Malley (2005) and in line with a descriptive-analytical method commonly employed in narrative reviews and qualitative studies (Parè et al., 2015). We recorded the following information: author(s); year of publication, title; research context; methodology; aims of the study; and how 'sociotechnical systems' were understood and applied, based on the theoretical and analytical foundations of the work and its findings. See Table 1 for an overview of the included articles.

Table 1. Overview included articles

Aven & Ylönen (2018)	Brady & Naikar (2022)
Carden et al. (2019)	Hamim et al. (2020)
Harvey et al. (2018)	Haas et al. (2019)
Kee et al. (2017)	Kjestveit et al. (2021)
Lynch et al. (2021)	Malatji et al. (2019)
Meacham (2022)	Naikar & Elix (2021)
Read et al. (2016a)	Read et al. (2016b)
Read et al. (2018)	Read et al. (2020)
Salwei & Carayon (2022)	Thoroman et al. (2018)
Thoroman et al. (2019)	Waterson et al. (2017)
Zhao et al. (2016)	

4. Results

In the following analysis, we aim to identify the theoretical foundations of the 21 studies included in the scoping review, their relationship to STS theory, and how they inform the design, analysis, or evaluation of safety-related systems. The analysis reveals a broad range of understandings of the term socio-technical systems. Across the sample, it appears in different roles: as an explicit theoretical foundation, as a background orientation toward complexity, or as an implicit logic embedded in system-level tools or design practices.

This chapter presents the findings thematically, beginning with studies that directly engage STS theory and progressing to those that draw on its assumptions more indirectly. In doing so, we aim to illustrate how STS thinking is reflected, whether explicitly or implicitly, in contemporary safety science research.

4.1. *Theoretical foundations*

Several studies directly engage with core principles of socio-technical systems theory, grounding their research into concepts such as joint optimization, user participation, and interaction between technical and social elements. A prominent group of contributions comes from researchers affiliated with the Centre for Human Factors and Sociotechnical Systems in Australia. Across a series of studies (Read et al., 2016a, 2016b, 2018, 2020; Carden et al., 2019; Thoroman et al., 2018, 2019), they apply STS in combination with Cognitive Work Analysis (CWA) to explore road safety, regulatory systems, and incident reporting.

These studies are notable for distinguishing between systems thinking and socio-technical theory, and for offering structured design tools such as the CWA Design Toolkit (CWA-DT). STS principles are integrated into both the analysis and development of safety-related interventions, with a particular emphasis on participatory design and user involvement.

Other studies also build explicitly on STS theory. Haas et al. (2019) apply STS to mining safety, focusing on the introduction of dust-control technologies. They emphasize the role of communication and collaboration in shaping outcomes during technology implementation. Similarly, Meacham (2022) conducts a literature review of STS theory and discusses its potential relevance to fire safety.

Conceptual contributions, such as Aven and Ylönen (2018), propose an integrated view of STS and risk governance, suggesting that safety is not a standalone outcome but rather a product of broader organizational interactions. Malatji et al. (2019), writing in the context of cybersecurity, propose a model for analyzing social, technical, and environmental practices using STS principles.

4.2. *Socio-technical systems as implicit or partial inspiration*

Several studies reference STS in general terms or reflect some of its underlying assumptions, but do not explicitly aim to contribute to a theoretical development. However, these contributions share a systems perspective, often emphasizing the interconnectedness of actors, technologies, and contexts. For example, Salwei & Carayon (2022) present a framework for socio-technical integration of artificial intelligence in healthcare. While STS is not deeply theorized, the study emphasizes iterative design, collaborative learning, and cross-level interactions, all of which align with socio-technical thinking.

Naikar & Elix (2021) draw on cognitive systems engineering to explore adaptability in military work systems. Although the conceptual basis is rooted in CWA rather than STS per se, the emphasis on flexible coordination, local autonomy, and context-aware design resonates with the principles of STS. Kjestveit et al. (2021) employ a work system model to investigate occupational injuries in Norwegian agriculture, emphasizing the intersection of diverse technical, environmental, and social factors within farming contexts. They emphasize organizational design and implicitly relate it to STS characteristics.

Harvey et al. (2018) examine risk-taking behavior among construction workers and identify how systemic pressures, such as transient employment structures and economic constraints, shape individual decision-making. Their call for participatory approaches and integrated models of causation suggests an alignment with STS theory, though the theoretical basis is only briefly mentioned. Zhao et al. (2016) refer to STS in their theoretical framing but primarily rely on quantitative subsystems analysis in their empirical work on macroergonomic modeling of injury risks in construction.

4.3. *System tools aligned with socio-technical systems logic*

A third group of studies employs system-oriented methods, such as AcciMap or Cognitive Work Analysis, that reflect STS-compatible thinking, even when STS theory is not explicitly stated. These tools are often used to trace causal relationships across organizational levels or to structure systemic analyses of safety issues.

AcciMap is central to five of the reviewed studies (Brady & Naikar, 2022; Kee et al., 2017; Hamim et al., 2020; Lynch et al., 2023; Waterson et al., 2017). Although initially inspired by Rasmussen's risk management model, these applications often focus on mapping multilevel interactions and identifying latent conditions in organizational systems. For instance, Kee et al. (2017) and Hamim et al. (2020) use AcciMap in participatory workshops to support shared understanding and system improvement, particularly in the context of transport safety.

Thoroman et al. (2018, 2019) examine near-miss reporting systems and assess their alignment with systems thinking. They argue that although most systems capture data across organizational levels, they fall short in supporting feedback, learning, or redesign, areas where STS perspectives might offer additional value. Although these studies rarely refer to STS theory directly, they share a system-level orientation and often work within methodological traditions (e.g., CWA, AcciMap) that emerged alongside or were influenced by sociotechnical thinking.

4.4 *Applications in design and practice*

Some studies apply socio-technical ideas to real-world design and implementation challenges. These contributions are often practice-oriented, with a focus on translating systemic insights into concrete interventions. Brady & Naikar (2022), working in the context of future Air Force systems, integrate design principles such as autonomy, creativity, and adaptability, terms consistent with STS literature, into a framework for managing work system complexity. Meacham (2022) discusses how a socio-technical perspective can enhance fire safety engineering by identifying unintended consequences of design choices that span system boundaries.

In other examples, practical design challenges are addressed through participatory or interdisciplinary approaches. Harvey et al. (2018) stress the importance of stakeholder dialogue and shared problem framing in construction, while Salwei & Carayon (2022) emphasize continuous co-development of AI-based systems in healthcare. These studies do not always identify themselves as STS-informed, but they often embody key principles such as stakeholder engagement, adaptive capability, and attention to dynamic interdependencies.

5. Discussion

This scoping review shows that the term 'socio-technical systems' is used in various and often inconsistent ways within the safety science literature. While some studies clearly engage with STS theory as an analytical and design-oriented framework (e.g., Read et al., 2016a, 2016b, 2018, 2020; Carden et al., 2019), many others use the term more loosely to describe the complexity of fields like construction, energy, or healthcare, without explaining how social and technical elements are theoretically connected.

This echoes earlier critiques (Waterson et al., 2015; Polojärvi et al., 2023) that the concept risks losing its effectiveness as an analytical tool when used without reference to its theoretical foundations. The discussion below addresses some practical implications of this varied and often inconsistent use of the term.

There is considerable variation in how ’systems’ are understood. Some studies adopt a structured and functionalist concept of a system, closely aligned with Rasmussen’s risk management framework (Waterson et al., 2017; Brady & Naikar, 2022) and tend to focus on hierarchical levels, decision flows, and interactions across clearly defined system components. The AcciMap appears particularly helpful in scenarios in which risks arise from top-down pressures and trade-offs, such as regulatory oversight or corporate governance (e.g., Kee et al., 2017; Hamim et al., 2020).

Other studies adopt more flexible and adaptive interpretations of systems. The work of Read et al. (2016a, 2016b, 2018, 2020) and Carden et al. (2019) is notable for combining systems thinking and STS theory in a manner that maintains the analytical structure of system models while emphasizing participatory and iterative design approaches. For example, their development of a Cognitive Work Analysis Design Toolkit (CWA-DT) incorporates STS principles by involving users in the co-design of public safety systems, including transportation and road infrastructure. These studies see systems as shaped by structure yet open to reconfiguration, aligning with the original socio-technical focus on open systems that evolve in response to environmental changes and social input.

A smaller group of studies adopts a constructivist perspective of systems as negotiated and emergent, often influenced by daily adaptation, interpretation, and local practice. For example, Salwei & Carayon (2022) propose a socio-technical framework for integrating artificial intelligence into healthcare that highlights continuous learning, collaborative development, and feedback loops between users, tools, and organizational structures. Haas et al. (2019) demonstrate that dust control technologies in the mining industry succeed when introduced through participatory processes that account for workers lived experiences. These studies reflect a view of systems as socially constructed and context-dependent, rather than as pre-established or designed solely from above.

Other studies also reveal conflicts between structured modeling methods and the complexity of socio-technical systems. For example, Thoroman et al. (2018, 2019) use AcciMap to examine near-miss reporting systems but find that reporting mechanisms are not designed to support learning or to capture the interactional dynamics that lead to incidents. Similarly, Zhao et al. (2016) apply a quantitative ergonomics model to analyze electrical injuries in construction but acknowledge that key interdependencies among technical, organizational, and social subsystems remain difficult to capture within formal modeling frameworks. These studies highlight the limitations of structured system views in environments characterized by rapid change and multiple overlapping pressures.

These different system interpretations align with broader ways of knowing and reflect an engineering-based system view: the system is limited, organized into layers, and its actions can be simplified and modeled for control purposes. The view supports decomposing functions and reflecting past actions, and it has been central to safety science. On the other hand, the original STS tradition at the Tavistock Institute emphasized that work systems are open, flexible, and shaped by the people within them. Here, the system is not something to be optimized from the outside, but rather something that evolves through participation, judgment, and shared reflection. The difference between fixed systems and changing, evolving systems is not merely philosophical; it matters, in practice, how safety is understood, managed, and designed.

STS emphasizes self-regulating teams, functional redundancy, and group autonomy. but few of the included studies directly engage with these ideas. Harvey et al. (2018), who discuss multidisciplinary collaboration in construction, are an exception. The literature review thus indicates that the role of team processes in shaping safety remains underexplored. This is a missed opportunity, particularly given the prominence of cross-functional teams in high-risk sectors.

Finally, there is limited engagement with the implications of digital transformation, despite its increasing relevance, as pointed out by Patricia et al. (2021). Only a handful of studies explicitly consider how AI, automation, or distributed infrastructures are reshaping system boundaries and human roles (e.g., Salwei & Carayon, 2022; Brady & Naikar, 2022; Malatji et al., 2019). These technologies challenge established assumptions about what constitutes a system, who participates in it, and how it can be governed. STS, with its emphasis on human-centered, ethical, and adaptive design, is particularly well positioned to address these challenges, provided that it is applied with theoretical clarity and practical intent.

6. Conclusion

This review underscores that a socio-technical systems perspective remains relevant and productive, provided it is applied with attention to its underlying assumptions and design principles. Differences in how systems are understood, as fixed structures to be modeled or as evolving practices to be co-created, shape both the scope of analysis and the kinds of safety interventions considered possible. Future research would benefit from more explicit reflection on these assumptions, stronger alignment between theory and method, and deeper engagement with the participatory ethos at the heart of STS theory.

This paper provides an initial understanding of the scope and nature of the existing literature and an impression of how the term "socio-technical systems" is used in safety research. The inconsistencies and often weak theoretical basis indicate a knowledge gap and the need for a more systematic review. Future research should prioritize explicit articulation of these assumptions, strengthen coherence between theoretical frameworks and methodological choices, and embrace the participatory ethos central to STS theory. Further research should deepen understanding of how socio-technical systems principles are applied not only within safety science but also across other research domains, to identify transferable insights and broaden their impact.

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