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Exploring Systems Thinking and System Dynamics in Fire Safety Engineering: A Literature Review

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Abstract The increasing complexity in the Fire Safety Engineering (FSE) field requires the adoption of risk assessment and safety management methods which address such complex behavior. In this context, complexity refers to systems of multiple interacting components where non-linear and adaptive relationships generate emergent behaviors, i.e., outcomes that cannot be anticipated solely by examining the individual parts. Systems Thinking (ST), including tools such as System Archetypes, Causal Loop Diagrams, and System Dynamics (SD) modeling, offers a holistic framework to address these challenges. This article presents a literature review on the application of ST and SD in FSE, focusing on its use in enhancing fire safety for buildings and infrastructures by identifying key trends, methodologies, challenges, and future research directions. A six-stage framework is adopted for the literature review which examines the development of ST in FSE. In total 35 studies were found as relevant for the FSE field due to their application of at least one ST tool. However, challenges such as the complexity of modeling large-scale systems, the need for high-quality data, and the integration of SD with other fire safety engineering methods remain. Overall, this review underscores the value of ST as a powerful tool for addressing the complexities of FSE, testing the effectiveness of different safety measures, and improving risk assessment in various environments, while highlighting that its potential usage has not been fully developed yet.

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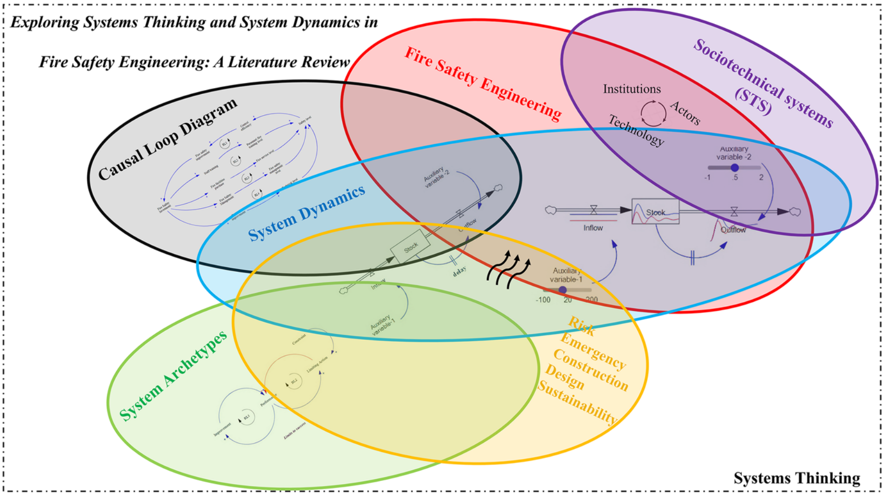
Graphical Abstract



Keywords Fire safety engineering · System dynamics · Systems thinking · Risk assessment · Safety management · Decision making

1 Introduction

Fire Safety Engineering (FSE) is a multidisciplinary field that integrates thermodynamics, fluid mechanics, material science, human behavior, risk assessment, and structural engineering to protect life, property, and the environment from fire hazards through the design of protection systemsand emergency strategies [1–3]. Fire safety relies on active measures—such as detectors, alarms, sprinklers, and extinguishers—that automatically detect and suppress fires [4], and passive measures—such as fire-resistant walls, doors, and compartmentation—that limit fire spread, preserve structural stability, and provide safe evacuation routes [3]. The interaction between these systems is essential for effective fire control [5], while consideration of human behavior ensures evacuation strategies supported by signage, lighting, and communication guide occupants to safety [6–9].

Fire risk assessment identifies hazards, evaluates consequences, and determines measures to reduce risks by analyzing fire likelihood, vulnerabilities, and potential impacts on people and property; it is carried out during design and updated as use, occupancy, or regulations change, guiding decisions and prioritizing safety interventions [10]. FSE is also shaped by national and international standards, such as NFPA codes in the USA and European Standards (EN), which prescribe requirements for protection systems and their design, installation, and maintenance [5, 11].

Traditionally, FSE has relied on well-established principles, empirical data, and regulatory frameworks to propose fire safety solutions [12, 13]. However, the complexity of modern buildings, urban environments, and the interdependencies within fire safety systems demand a framework which considers the feedback effects present in FSE [14, 15].

As the field has been evolving, several authors have recognized the need for more holistic, systems-based approaches within FSE. Early contributions by Beard [16] and Santos-Reyes & Beard [17, 18] highlighted the importance of considering the interplay between technical, human, and organizational factors. Subsequent works, such as Bjelland [19], and Gehandler [20], further emphasized risk governance, systemic perspectives, and the integration of multidisciplinary insights into fire safety practice. More recently, calls have been made for integrating Systems Thinking (ST) into FSE frameworks [15, 21]. In this paper, ST is understood at three levels: (i) as a philosophical perspective emphasizing interconnections, feedback, and emergence; (ii) as a methodological approach expressed through frameworks like System Dynamics (SD); and (iii) as a toolset including Causal Loop Diagrams (CLDs) and System Archetypes (SAs) [22–26].

The ST paradigm has been widely used in different fields worldwide from business management to medicine, and engineering [27]. One of the main advantages of its application is that it provides a holistic view of the analyzed system [28–30]. Using a ST approach provides insight for decision-making and developing long-term solutions to complex problems [31]. The integration of the *Complexity* and *Sustainability* paradigms, and their interactions, with the ST approach furthermore provide several benefits [28, 31]. ST also provides the tools for exploring the complex interactions of a given system, i.e., SAs, CLD, and SD models [27, 31]. Moreover, SD can be integrated with other tools by modeling the dynamic behavior of variables [31–33].

ST is currently not yet a common conceptual framework within FSE, but there have been applications of specific methodologies and tools in selected contexts. For example, Meacham et al., [21] proposed a framework for advancing performance-based design (PBD) for fire safety and move towards a Socio-technical systems (STS) approach. STS theory originated in the work of Emery & Trist [34], who explored the complex interdependencies between social actors and technological systems in organizational settings. These early studies recognized that real-world systems are inherently complex, adaptive, and shaped by both human and technical elements, thus challenging the adequacy of purely technical or reductionist approaches [22, 35]. STS perspectives were developed to address this complexity, emphasizing joint optimization of social and technical subsystems and acknowledging that changes in one inevitably affect the other. This foundational understanding underpins more recent applications of STS to FSE, where buildings and infrastructures can be viewed as socio-technical entities whose fire safety performance emerges from the interaction of people, technology, and regulatory frameworks [36]. STS development focused on optimizing the interaction between employees, organizations, and new technologies [37]. Variations of STS theory have been influenced by disciplines such as psychology, sociology, engineering, political science, and economics. STS theories have been applied, additionally, to areas such as accident analysis, risk management, interactions between building-hazards and regulation, and critical infrastructure interdependencies [38, 39].

ST also offers a powerful methodology for understanding and managing the complex interactions within (fire safety) systems through the implementation of SD [27, 31]. Unlike traditional linear approaches, SD thus enables fire safety engineers to model the interconnected components of a fire safety system as a whole, considering feedback loops, delays, and non-linear behaviors [32, 33]. This holistic perspective is essential for capturing the emergent behavior and properties of fire safety systems, such as, the spread of fire, the effectiveness of suppression methods, and human evacuation behaviors, which are often difficult to forecast using conventional techniques [4, 40]. The application of SD in FSE offers several advantages as it facilitates the development of more robust models for simulating real-world scenarios, helping engineers and decision-makers to anticipate potential issues before they arise [5, 41].

This article aims to review and synthesize existing literature studies on the application of ST and SD in FSE for buildings and infrastructures, by identifying key trends, methodologies, challenges, and research directions. Special emphasis is placed on providing a review on the application of STS theory to FSE and on discussing developed SD models. In addition to ST, SD, and STS approaches, other systems-oriented perspectives are highly relevant to fire safety. These include safety systems approaches, such as Leveson's STAMP, CAST, and STPA [42], and resilience thinking [43, 44] which emphasizes the adaptive capacity of systems to anticipate, respond, and learn from disruptions. Although not the focus of this review, these approaches provide complementary insights and underscore the breadth of systems-oriented work in safety science.

1.1 Research Aims and Research Questions

As indicated in the problem description above, the application of ST and SD in FSE can provide important methodological and modelling benefits considering the increasing complexity of modern buildings and urban environments. There is, however, a lack of consolidated knowledge on how these methods have been applied to date, and on the opportunities they offer for addressing emerging fire safety challenges.

This literature review aims to:

1. Systematically identify and synthesize existing studies applying ST tools in FSE.
2. Analyze the methods, contexts, and outcomes of these applications.
3. Identify gaps, challenges, and future research opportunities for integrating ST approaches into FSE practice.

Research questions (RQ) guiding this review are:

- RQ1: How has Systems Thinking, including SD, been applied to date in the context of Fire Safety Engineering?
- RQ2: What are the main benefits and limitations reported in these applications?
- RQ3: What research gaps and opportunities exist for further integrating ST approaches into FSE?

1.2 Paper Structure

The structure of this literature review is as follows: Sect. 2 provides a theoretical background for understanding the principles of ST, SD, and STS. Section 3 contains the methodological framework adopted for the literature review. Section 4 discusses relevant literature that developed or adopted SD modeling in fire safety, or can serve as a source of information for such SD modeling. Additionally, a detailed discussion of the main SAs, Feedback loops, CLD, and SD is provided. Section 5 identifies gaps and opportunities for future work as well as the challenges and limitations associated with it. Finally, Sect. 6 presents the conclusions from this literature review and recommendations for advancing the integration of SD in FSE. Although some of the initial content may be familiar to readers within FSE, this introduction aims to also serve readers from other domains—especially those versed in ST—by establishing the necessary FSE context for the interdisciplinary exploration that follows.

2 Theoretical Background

This section provides a theoretical overview of ST, SD, and STS theory to establish the conceptual foundation for the literature review. These frameworks are presented as established methodologies rather than being subjects of critical examination. The focus of this paper is not to evaluate or compare ST, SD, or STS with alternative systems theories, but rather to review how they have been applied in the context of FSE. While this is a deliberate choice to maintain focus, it does represent a boundary of this study. Exploring alternative or complementary perspectives to ST and SD could be a valuable direction for future research. Additionally, the tools that can be used within an ST framework are explained, such as the CLD, SAs, and SD.

ST encompasses a range of philosophical and methodological perspectives that vary in their emphasis on qualitative or quantitative analysis. Two influential perspectives are often highlighted:

- Soft/phenomenological systems approaches—Exemplified by the work of Checkland [22], this perspective emphasizes understanding systems through the lens of stakeholders' perceptions, experiences, and values. Known as Soft Systems Methodology (SSM), this approach focuses on clarifying complex, ill-structured problems by engaging stakeholders in iterative learning processes. It is particularly suited for situations where problem boundaries and objectives are contested or evolving.
- Hard/quantitative systems approaches—Represented by Forrester's System Dynamics [23], this perspective is grounded in formal modeling and simulation of feedback processes. It seeks to capture the structure and behavior of systems through quantifiable variables, causal relationships, and time delays. This approach is effective in contexts where system boundaries can be defined and sufficient data exist to support modeling.

Other foundational contributions to ST include von Bertalanffy's [35] General System Theory, which provided the theoretical basis for viewing systems holistically; Meadows' [24] articulation of feedback loops and leverage points in Thinking in Systems; and Senge's [25] integration of ST into organizational learning.

In this review, both perspectives are relevant: the soft systems view offers insight into socio-technical and stakeholder dimensions of fire safety, while the hard systems view informs quantitative modeling through tools such as SD. Integrating these perspectives enables a more comprehensive approach to complex problems in FSE, where both stakeholder engagement and quantitative analysis are often necessary.

It is important to clarify the boundaries of ST when combining it with other analytical approaches. As Leveson [42] notes, ST analyses focus on understanding system structure, feedback loops, and interdependencies, whereas traditional risk analyses quantify probabilities and consequences, often within a predefined event space. In this review, ST-based tools are understood to include SD, CLDs, and SAs. Non-ST tools such as CBA, Probabilistic Risk Assessment (PRA), or Bayesian Networks can complement ST when carefully integrated—for example, using SD to map dynamic interactions and PRA to quantify specific risk pathways. Such combinations can provide a more comprehensive view of system performance, but also introduce methodological challenges, including the need to reconcile qualitative causal mapping with quantitative statistical modeling. Recognizing these boundaries helps prevent the misconception of ST as a 'theory of everything' and ensures its application remains problem-focused and evidence-based.

2.1 Systems Thinking Approach and Interactions with Complexity and Sustainability Paradigms

ST can be understood at the philosophical level as the holistic conceptual framework for analyzing systems by recognizing feedback loops, interdependencies, and emergent properties [22, 24, 35]. 'System Dynamics' (SD), developed by Forrester [23], is a quantitative simulation method within the ST paradigm (i.e., the methodological level of ST), translating conceptual models into computational representations to test policies over time. SAs represent recurrent behavioral patterns in systems [25] (toolset level of ST), while STS theory views systems as the product of interactions between social and technical components [34]. These definitions form the conceptual basis for the analyses presented in this review.

Thus, while ST is a broad conceptual framework for understanding the interconnections within complex systems, SD is a specific methodological tool within that framework. ST helps identify relationships, feedback loops, and leverage points conceptually, often using qualitative tools like CLD. In contrast, SD takes this a step further by translating these relationships into quantitative models that simulate system behavior over time. In other words, ST frames the problem and structure, while SD allows for computational modeling and scenario testing.

For example, consider an FSE scenario involving an automatic sprinkler system in a commercial building. A ST approach would help identify the system elements (e.g., detection, water supply, maintenance routines) and map out their interrelations, such as how delayed maintenance reduces system effectiveness over time. Building on this, a SD model could simulate how sprinkler effectiveness evolves based on factors such as maintenance frequency, detection accuracy, and fire growth rate. This simulation would help engineers test the long-term impact of different maintenance schedules on fire suppression performance, allowing them to optimize intervention strategies and allocate resources more effectively.

ST is a structured approach to address complexity. The Complexity paradigm recognizes that many real-world systems, including those related to fire safety, exhibit hardly predictable behaviors due to their intricate structures and interactions [28]. More explicitly, complexity is understood as a property of systems in which numerous interdependent elements interact in dynamic and/or non-linear ways, leading to emergent patterns that are not directly traceable to individual components [22, 24]. In the FSE context, such complexity may manifest in scenarios where technical systems, human actors, and regulatory frameworks interact—such as during an emergency evacuation—producing outcomes that are difficult to predict using reductionist approaches. ST allows decision-makers to account for these complexities by modeling the system as a whole, from a holistic perspective, rather than analyzing components in isolation [45].

As touched upon earlier with regard to ST, in this review, Systems Thinking (ST), Complexity, and Sustainability are considered across three levels of understanding (Table 1). At the philosophical level, ST represents a worldview emphasizing interconnections, feedback, and emergence; Complexity reflects a scientific perspective on adaptive, non-linear systems; and Sustainability provides a normative vision for long-term viability. At the methodological level, ST is expressed through approaches such as System Dynamics, qualitative system mapping, or hybrid socio-technical modeling; Complexity is treated as a conceptual orientation for analyzing interdependent system behavior; and Sustainability is framed as a principle guiding assessment methods and design strategies. Finally, at the tool level, ST is operationalized through techniques such as Causal Loop Diagrams (CLDs), System Archetypes (SAs), and simulation models; Complexity is represented through indicators or metrics of interdependence and adaptivity; and Sustainability is applied through tools like life cycle assessment, resilience metrics, or multi-criteria evaluation frameworks.

This multi-level framing highlights how these perspectives interact in Fire Safety Engineering: philosophical principles shape methodological choices, which are then implemented through practical tools. This distinction is particularly relevant for fire safety challenges that require balancing immediate performance with long-term resilience [28] and aligns closely with recent work on dynamical systems modeling in social–ecological systems [46]. For example, choosing suppression agents for fire suppression systems requires a deep understanding of how these agents impact ecological health and resource use [47]. Similarly, evacuation strategies must consider the diverse needs of different populations by ensuring equitable protection for all building occupants [48, 49]. ST thus fosters a proactive approach to sustainability by modeling how interventions affect both immediate outcomes and lifecycle performance [50].

Table 1 Definition of terms and representation of concepts covered in this article considering three levels of understanding

Term	Philosophical level	Methodological level	Tool level
Paradigm	Overarching worldview or conceptual lens for interpreting systems and problems	N/A	N/A
System	Conceptual model of interacting elements forming a whole	Frameworks for analyzing system boundaries, interactions, and functions	System maps, stock-and-flow diagrams, network representations
Systems Thinking (ST)	A worldview emphasizing interconnections, feedback, emergence, and holistic framing [22–26]	Approaches such as System Dynamics, qualitative system mapping, hybrid socio-technical modeling	Causal Loop Diagrams (CLDs), System Archetypes (SAs), simulation models
Complexity	Perspective on adaptive, non-linear, emergent system behaviors	Conceptual orientation to study interdependence and dynamics in FSE	Complexity indicators, resilience measures, sensitivity analyses
Sustainability	Normative paradigm guiding design toward long-term viability	Assessment methodologies such as life cycle analysis, resilience frameworks, or multi-criteria evaluation	Tools like LCA software, sustainability metrics, cost–benefit models
Socio-technical systems (STS)	Perspective integrating social and technical subsystems	Analytical frameworks to study human–technology–institution interactions in FSE	Socio-technical models, agent-based simulations, stakeholder mapping

Overall, the integration of these three paradigms ST, Complexity, and Sustainability, may foster the development of fire safety solutions that are efficient, resilient, adaptable, and aligned with long-term sustainability goals.

2.2 Socio-technical Systems (STS) an Emerging Approach for FSE

Buildings and infrastructures can be viewed as Socio-Technical Systems (STS), where performance emerges from interactions among actors, components, and regulatory processes, making fire safety design a sociotechnical challenge rather than a purely technical one [21, 37, 48, 51]. This perspective represents a paradigm shift in performance-based design (PBD), emphasizing the safe operation of the building or infrastructure throughout its lifecycle rather than merely achieving regulatory approval [51]. Originating from studies of organizational dynamics, STS theory highlights interdependencies between social and technological elements across three levels: primary work systems (e.g., a sprinkler system installation), organizational systems (e.g., the processes governing the operation of the building), and macrosocial systems involving wider institutions and communities (e.g., fire and rescue service) [51, 52]. The theory recognizes that multiple stakeholders with diverse goals continuously reshape systems, which—unlike centrally designed technologies such as smartphone operating systems—cannot be fully controlled or fixed but evolve through these interactions [37, 51].

The emerging complexity in FSE can according to STS theory be addressed by the study of the interrelations among societal, regulatory, and technological aspects. This STS vision is aligned with the main focus of this review article, because it offers a new framework for applying a ST paradigm to FSE, and provides a pathway for exploring the interdependencies among the Complexity, Sustainability, and ST paradigms, which were discussed in the previous subsection. The quantitative study of system interrelations as well as their complex dynamics is within the scope of SD modeling.

It is relevant to highlight as part of this review that related systems-based approaches have been influential in safety science. Leveson's Systems-Theoretic Accident Model and Processes (STAMP), along with CAST and STPA, provide structured methods for analyzing accidents and hazards within a systems-theoretic framework [42]. Similarly, the field of resilience engineering highlights system adaptability, learning, and robustness under uncertainty, with foundational contributions from Woods [43] and Hollnagel et al. [44]. These approaches align with many principles of ST and could enrich fire safety research through integration with FSE practices (see also Salmon et al., [26]). In the context of FSE, early frameworks such as the NFPA 550 Fire Safety Concepts Tree [53, 54] provided structured approaches for conceptualizing fire safety design. While not fully aligned with the ST perspective adopted in this paper, they can be seen as important precursors that shaped the evolution of system-based thinking in FSE.

In conclusion, the STS perspective offers a compelling lens for understanding fire safety as an emergent property of the interplay between social and technical components. This may appear at odds with current building codes which often (nominally) enforce simple requirements —such as requiring full evacuation without assistance or disregarding fire service intervention for structural fire protection. This does not constitute a limitation of the STS approach, however. On the contrary, STS approaches allow to evaluate the "real" system performance given the nominally enforced requirements. Thus, while the STS framework is not intended to replace current regulations, it can (i) complement performance-based design by encouraging a broader view of fire safety that includes interdependencies often overlooked by traditional methods, and (ii) provide input towards improving the effectiveness of regulatory requirements.

2.3 System Archetypes: Structure and Meanings

SAs are recurring patterns of system behavior that can be observed across various complex systems, regardless of their domain [55–57]. These archetypes provide insight into the underlying structures that drive system behaviors, enabling practitioners to recognize and address issues more effectively. As stated in [58, 59] with regard to the construction industry in general, understanding SAs can provide a clear visualization of the main interactions among safety, accident investigation, and productivity. Applied to FSE, such improved insight can contribute to the design of more robust fire safety strategies. SAs are built upon feedback loops (both reinforcing and balancing) and illustrate how a system's structure leads to specific behavioral patterns. Figure 1 shows specific SAs architecture. By identifying these SAs within fire safety systems, engineers can gain a deeper understanding of why certain problems persist and how interventions might produce unexpected outcomes [57]. Table 2 elaborates on these SAs and their relevance to FSE.

Understanding and identifying SAs in FSE provides several opportunities. First, it allows engineers to anticipate and mitigate common pitfalls that may arise in complex fire safety systems. For example, recognizing the "Shifting the Burden" archetype can help prevent overreliance on temporary fixes by encouraging the development of long-term, root-cause solutions. Similarly, awareness of the "Limits to Growth" archetype can lead to more sustainable fire safety designs that account for system limitations and prevent deterioration over time.

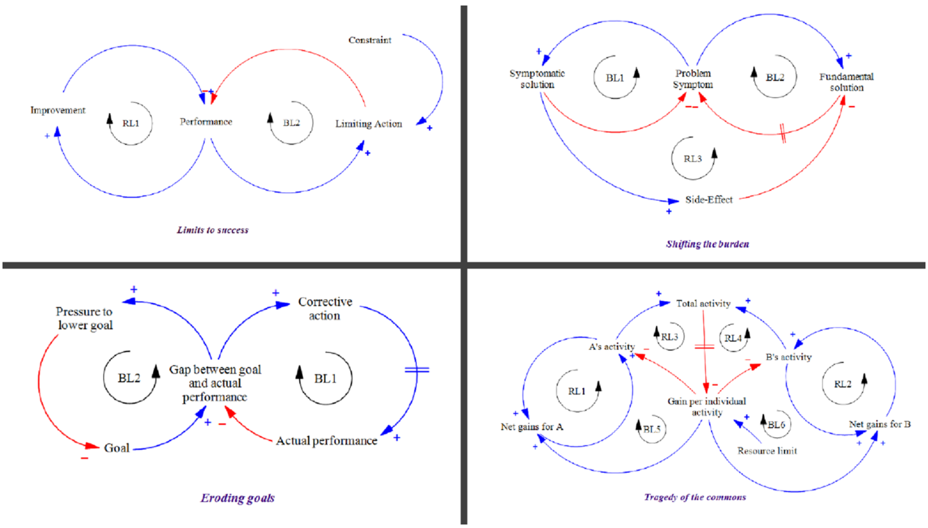


Fig. 1 System Archetypes architecture. The arrows indicate the polarity of the causality: positive (in blue) (indicating an increasing effect), or negative (in red) (indicating a reducing effect)

Table 2 Potential applications of relevant SAs to the FSE field

System Archetype [55, 56]	Structure	Possible meaning/application in FSE
Limits to success—Growth initially occurs but slows or reverses when a limiting factor or constraint is reached (e.g., safety interventions improving evacuation efficiency may plateau due to physical bottlenecks)	A reinforcing loop (RL) initially drives the system *performance* toward growth or *improvement*, but a balancing loop (BL) eventually counters this growth due to constraints or limits (*limiting action*) within the system. The RL and the BL are connected, with the latter being triggered by the system reaching its limits	This SA can appear when the introduction of additional fire protection measures initially reduces the fire risk. However, as more safety measures are introduced, factors such as limits to maintenance (e.g., due to limited maintenance resources) or unforeseen limitations (e.g., evolving fire risks due to the introduction of new materials which are not targeted by fire safety measures available on the market) can stop further risk reduction Recognizing this archetype helps engineers design systems that account for long-term sustainability and maintenance needs
Shifting the burden—reliance on short-term fixes diverts attention from long-term solutions (e.g., increased reliance on suppression systems rather than addressing underlying fire risks).	This archetype involves two feedback loops: a *symptomatic solution* that provides immediate relief (but addresses only the symptoms of the problem) and a *fundamental solution* that targets the root cause. Overreliance on the symptomatic solution can weaken the system's tendency to implement the fundamental solution, leading to reduced system performance.	This archetype can manifest when short-term fixes (e.g., increasing a product classification requirement) are implemented to address fire hazards without addressing the underlying issues (e.g., poor building design or inadequate fire prevention measures). Relying too heavily on these quick-fix solutions may prevent the development of more effective, long-term fire safety strategies, leading to a cycle where the underlying risk remains unaddressed
Eroding goals—performance standards are gradually lowered when goals are not met, leading to long-term decline (e.g., fire safety codes are relaxed over time to reduce costs, resulting in progressively lower safety levels)	This archetype occurs when there is a *gap* between the desired performance (*goal*) and the *actual* performance. Instead of addressing the root causes of underperformance, the system lowers its goals or standards, leading to a downward spiral.	This archetype can be seen when fire safety standards are compromised over time due to cost pressures, lack of enforcement, or complacency. Recognizing this archetype allows engineers and policymakers to resist the temptation to lower safety standards and instead focus on continuous improvement.
Tragedy of the Commons-Individual actors overuse shared resources, reducing system performance (e.g., reliance on fire and rescue service to achieve adequate safety).	This archetype involves multiple actors sharing a common resource. Each actor seeks to maximize their benefit (*gains*), leading to overuse of the resource and eventual depletion, harming the entire system.	This archetype can occur in scenarios where multiple stakeholders share responsibility for fire safety in a building or community, such as in mixed-use developments or urban planning. Each stakeholder may prioritize their interests (e.g., cost savings or maximizing space utilization), which can lead to collective neglect of fire safety measures. Recognizing this archetype helps in promoting collaborative fire safety efforts and shared responsibility.

The System Archetypes presented here are adapted from established literature [24, 25, 60] and selected for their relevance to FSE contexts. They are not newly developed by the authors, but rather represent recurring patterns of system behavior that have been applied in this review to illustrate fire safety challenges

Moreover, SAs can be used as diagnostic tools to analyze existing fire safety challenges. By mapping the feedback loops and structures that underpin a particular problem, engineers can better understand why certain issues persist and how to intervene effectively. Hence, SAs provide a valuable framework for understanding the recurring behavior patterns in fire safety systems, anticipating unintended consequences, and creating interventions that address root causes rather than symptoms. Finally, different SAs can be properly connected within a CLD, which can in turn be further transformed into an SD model.

2.4 Causal Loop Diagrams, A Visualization Tool for Complex Interactions

CLDs are powerful tools used in ST for visualizing and understanding the complex interactions within a system. CLDs provide a graphical representation of how different variables within a system influence one another through feedback loops, helping to identify the dynamic behavior of the system over time. CLDs are ideal for dealing with complex systems because they allow to consider simultaneously interconnected factors, assess risks, predict outcomes, and therefore, inform effective interventions [31].

At the core of a CLD are variables, which represent anything from a physical quantity (such as temperature, and smoke concentration) to more abstract concepts (such as perceived safety or response time). These variables are connected by arrows that indicate the polarity of the causality. A positive causality between two variables (“A” and “B”) means that (all else remaining equal) an increase in the variable “A” will lead to an increase in the value of the variable “B” above what it would otherwise have been. On the contrary, a negative causality means that an increase in the variable “A” will lead to a decrease of the value of the variable “B” below what it would otherwise have been. The connections between variables form feedback loops, which can be reinforcing (positive feedback) or balancing (negative feedback) [33].

In FSE, CLDs can thus help model complex interactions that are difficult to capture using traditional linear approaches. A good example is considering a scenario involving fire spread in a building. A CLD can visually represent how factors such as fuel availability, ventilation, and suppression systems interact with one another to influence fire growth [61, 62]. Feedback loops can illustrate how an increase in fire intensity leads to higher temperatures, which, in turn, accelerates combustion (reinforcing loop). At the same time, a balancing loop captures how the activation of sprinklers can reduce the fire’s intensity, thus controlling its spread. These CLDs make it easier to identify which variables are key drivers of the system’s behaviour and how interventions may ripple through the system [63].

Additionally, one of the primary advantages of CLDs is their ability to simplify complex systems into a more digestible format, making it more feasible for engineers, policymakers, and other stakeholders to communicate and collaborate effectively. By visualizing the relationships and feedback loops within a fire safety system, CLDs allow stakeholders to better understand how different interventions (such as changes in building materials, fire suppression methods, or evacuation strategies) will impact the overall system. This clarity helps in decision-making processes, ensuring that actions taken to improve fire safety are informed by a comprehensive understanding of the SD at play [55].

CLDs also serve as a foundation for developing simulation models, such as those used in SD-based models. By first mapping out the qualitative relationships between variables in a CLD, engineers can then move on to developing quantitative models that simulate the behaviour of the system under different scenarios. For example, a CLD of an evacuation process can highlight how crowd density, exit availability, and evacuation routes interact, which can then be translated into a more complex quantitative simulation to optimize evacuation strategies under various fire conditions [5, 6].

2.5 System Dynamics Overview: Flows, Stocks, and Delays

SD is a powerful quantitative modeling approach used to simulate the behavior of complex systems over time. Originally developed by Jay W. Forrester in the 1960s [32], it has since been applied across several fields, including economics, environmental studies, and engineering. In FSE, SD offers a framework to model the dynamic interactions within fire safety systems, allowing engineers to predict how different variables change over time, evaluate the impacts of policies, and optimize the overall system performance [14, 64].

Figure 2 shows the basic structure of a generic SD model. There are three main components in an SD-based model: stocks, flows, and delays. Also, there are auxiliary variables which simplify the definition of relationships for the simulation. Stocks represent the accumulation of resources, materials, or other quantifiable entities in a system at any given time. Stocks are essentially the "state" of the system and can be thought of as containers that hold quantities of something. In FSE, examples of stocks can include the amount of combustible material present in a building, the number of operational fire extinguishers, or the current temperature of a room during a fire event. Stocks change over time as they are filled or drained by flows (see below). Stocks represent the system's memory, storing information about past actions and conditions. They also provide inertia, meaning that changes in the system often occur gradually rather than instantaneously [32].

Flows represent the rates at which stocks increase or decrease. In other words, flows are the processes that fill or drain the stocks in a system. Flows can be seen as the movement of resources into or out of a stock over a certain time. Flows are driven by decisions, policies, physical processes, and external influences. Understanding the factors that influence flows is crucial for predicting the behavior of a fire safety system. For instance, the rate at which fire spreads (a flow) can be influenced by factors such as ventilation, fuel type, and fire suppression activities. Engineers can manipulate flows to achieve desired outcomes, such as slowing the spread of fire by increasing fire suppression efforts [31].

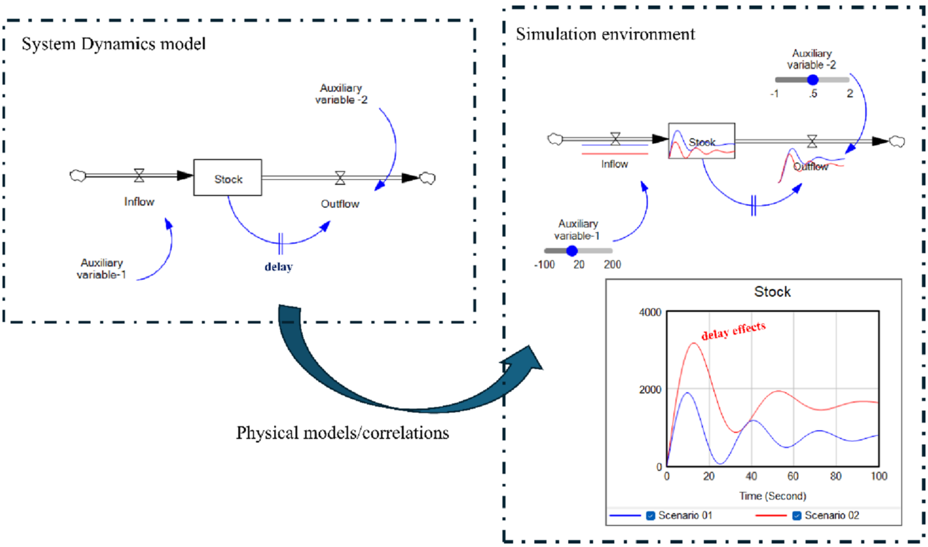


Fig. 2 System dynamics modeling process

Delays represent the time lag between an action or decision and its effect on the system. Delays are inherent in many real-world systems and can significantly influence system behavior, often contributing to unexpected outcomes. Delays can create instability and oscillation within a system, especially when feedback loops are involved. For example, in a fire evacuation scenario, a delay in the decision to evacuate can result in increased danger as conditions deteriorate. Identifying and accounting for delays is essential when designing fire safety interventions, as they can influence the timing and effectiveness of responses [5, 9].

The interactions between stocks, flows, and delays form the basis of dynamic behavior in systems. By mapping these interactions, SD models can capture the complex, non-linear behaviors often observed in real-world fire safety systems. This holistic view allows for the identification of critical points in the system where interventions can have the most significant effect, ultimately improving fire safety outcomes.

While SD modeling can most readily be applied in FSE to represent fire phenomena and safety system performance, it also has the potential to capture dynamics at the level of entire STS. By explicitly modeling the interactions between social, organizational, and technical components, SD could support analyses of how regulatory frameworks, occupant behavior, and emergency response interact with physical fire dynamics. Such applications have been explored in related fields, including social-ecological systems and infrastructure resilience [46], and could be adapted to FSE. However, modeling large STSs requires careful boundary definition, extensive data, and robust validation, which present both methodological challenges and opportunities for future research.

3 Methodology

This section explains the general framework employed in this literature review which is divided into six main stages: starting (stages 1–2), core (stages 3–4), and applications (stages 5–6). Stage 1 focuses on identifying the key terms essential for investigating the application of ST and SD in the FSE field. Stage 2 outlines the literature review methodology, including the filtering and selection of articles for analysis. Stage 3 outlines the main applications of the ST framework to FSE as derived from the identified studies and SAs. Stage 4 examines the identified studies for current applications of SD. Stage 5 proposes hypothetical applications of ST tools to FSE based on the existing state of the art. Finally, Stage 6 highlights future research directions by addressing the challenges and limitations of the approaches discussed, based on the current research needs for the FSE profession reported by SFPE [65]. Figure 3 illustrates the general framework proposed in this review article.

3.1 Stage 1: Identification of Keywords

The first stage involves identifying the primary keywords necessary for exploring the application of ST tools in the FSE field. In this literature review, the focus is on studying the use of SD in FSE. Therefore, a combination of ST-related keywords with FSE-specific keywords is considered (as shown in Table 3). The identification process is divided into two main steps. The first step focuses on studies that directly applied SD to FSE, while the second step includes studies that utilized an ST approach in related fields connected to FSE. In some cases, broader keywords (e.g., ‘sustainability’) were paired with ‘Systems

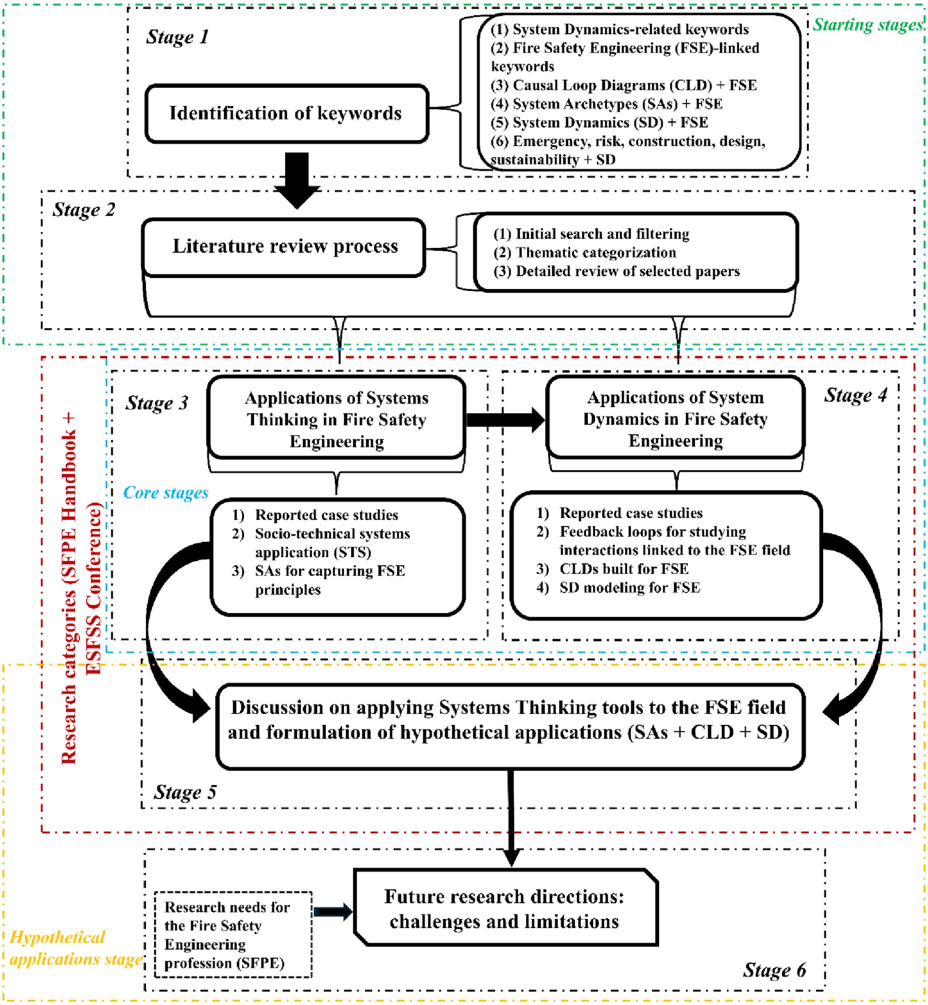


Fig. 3 Applied framework for the literature review

Thinking' or 'System Dynamics' to identify relevant studies in related domains, due to the limited number of direct applications in FSE. To maintain relevance, a two-step filtering process was implemented: (1) initial screening of titles and abstracts to confirm the use of a predefined ST tool and a safety-related context relevant to FSE, and (2) application of the inclusion criteria in Table 3, ensuring that the study either directly addressed FSE or could be reasonably adapted to it.

The keywords were used to search academic databases, including Scopus, Web of Science, Google Scholar, and IEEE Xplore, resulting in the identification of relevant peer-reviewed journal articles, conference papers, technical reports, and books. The literature search was conducted until February 2025. Two main search codes were applied. The first code—("Systems Thinking" OR "System Dynamics" OR "System Archetypes" OR "Causal Loop Diagram") AND ("Fire Safety Engineering")—yielded 191 results and tar-

Table 3 Combination of keywords in this literature review article

Combination of keywords	Systems thinking	System dynamics	System Archetypes	Causal loop diagram
Fire Safety Engineering	*Primary focus*			
	Aim: To explore the main studies which directly applied a Systems Thinking approach to the FSE field			
Risk	*Secondary focus*			
Emergency	Inclusion criteria: The article has to include at least one application of an ST tool that can be expanded to the FSE field. The study needs to contain a structured application of an ST tool related to fire safety, construction safety, risk management, emergency response, or sustainability in safety systems. The inclusion of papers in this category was stopped when it was observed that the inclusion of further papers in this category no longer influenced the (preliminary) conclusions drawn from the analyses			
Construction				
Design				
Sustainability				

In this review, 'ST tool' refers specifically to System Archetypes, Causal Loop Diagrams, System Dynamics, or the Socio-Technical Systems framework, as defined in established Systems Thinking literature and selected a priori by the authors. Broader search terms (e.g., "sustainability") were paired with 'Systems Thinking' or 'System Dynamics' to identify potential cross-domain studies. All results were screened and filtered to retain only those relevant to FSE or closely related safety contexts

geted studies directly linking ST tools to the FSE domain. The second code—("Systems Thinking" OR "System Dynamics" OR "System Archetypes" OR "Causal Loop Diagram") AND ("Specific field" AND "Fire Safety")—was run separately for each 'Specific field': Risk (1770 results), Emergency (1190 results), Construction (1560 results), Design (2190 results), and Sustainability (1160 results). After removing duplicates from the combined results, titles and abstracts were screened to confirm the use of at least one predefined ST tool in a safety-related context relevant to FSE. The full texts of the remaining papers were then reviewed according to the inclusion criteria in Table 3. This process resulted in 35 studies being retained for detailed analysis in this review.

3.2 Stage 2: Literature Review Process

This stage focuses on developing the literature review process. Initially, a first search and filtering of the identified studies is conducted, taking into account the aim and inclusion criteria outlined in Table 3. Specifically, for an article to be included, it must either directly apply an ST-related tool to the FSE field or present a developed model in a related field that adds value to FSE. For the purposes of this review, 'ST tool' refers to a predefined set of methodologies widely recognized in the ST literature: SAs, CLDs, SD, and the STS framework. These tools were selected a priori based on established definitions [60, 66]. Following the filtering, a thematic categorization is performed for clustering the identified studies depending on which ST tool has been used and if this is directly connected to FSE or considers a related field. Finally, a detailed analysis of the selected papers is conducted, which is further expanded upon in subsequent stages.

3.3 Stage 3: Applications of Systems Thinking in Fire Safety Engineering

This stage identifies the main applications of ST theory to FSE as identified through the literature search. For this purpose, the main studies which have conducted a theoretical or a practical application of ST are evaluated in depth based on their potential to be further expanded to an SD approach. Specifically, the following aspects are investigated: (1) reported case studies. (2) STS application, and (3) SAs for capturing FSE principles.

3.4 Stage 4: Application of System Dynamics in Fire Safety Engineering

In stage 4, a detailed analysis of key case studies is conducted considering their application of SD to the FSE field. The investigation focuses on the main feedback loops, CLDs, and SD models, as well as the availability of equations and performed simulations. Specifically, the following aspects are examined: (1) reported case studies; (2) feedback loops for analyzing interactions within the FSE field; (3) CLDs developed for FSE; and (4) SD modeling techniques for FSE. To group the results, research categories are adopted which cluster chapters from the *SFPE Handbook of Fire Protection Engineering* and key topics from the *European Symposium on Fire Safety Science* (ESFSS 2024) conference.

3.5 Stage 5: Discussion on Applying Systems Thinking Tools To the FSE Field and Formulation of Hypothetical Applications

This stage focuses on formulating possible applications of ST tools in the FSE field, based on the current state of the art identified in the previous stages. These potential applications are aligned with the previously defined research categories and with the research needs for the FSE profession proposed by SFPE [65].

3.6 Stage 6: Future Research Directions: Challenges and Limitations

The final stage aims to identify gaps in the current literature and outline potential future research directions, taking into account the challenges and limitations associated with the SD approach. Additionally, guidelines are provided to facilitate the exploration of each proposed research line.

4 State-of-the-Art of Applications of Systems Thinking and System Dynamics in Fire Safety Engineering

This section outlines the results of the literature review, considering the methodology outlined in Sect. 3.

4.1 Studies Included in this Literature Review Article (Stages 1–2)

This section presents the main results from Stages 1–2 of the applied literature review framework (see Fig. 3). The initial keyword searches yielded a large set of publications. Following the two-step filtering process described in Stage 1, this pool was narrowed to 35 retained studies that either directly addressed FSE or could be meaningfully adapted to it. Tables 4 and 5 show the retained studies. Figure 4 shows the categorization for each study depending on which ST-related approach was developed or adopted, the research field, and the interactions among tools, concepts, and keywords.

As can be noticed from Fig. 4, a limited number of studies have so far proposed an integration between ST tools such as CLD + SD and FSE. The most complete research studies included the development of a CLD and a further translation to a Forrester diagram (an SD model), such as in I, II, III, VIII, and IX [7, 67, 68, 72, 73]. Additionally, some studies developed SD models in the FSE field such as IV, V, VII, X, XI, XII, XIV, and XVI [69–71, 74–76, 78, 80]; while others only developed a CLD d such as VI, XIII, and XV [6, 77, 79]. These first 16 studies are directly connected to FSE. Moreover, there are eight other studies which meet the inclusion criteria proposed in this framework. These focused on fields related to the FSE, adopting at least one ST-related tool that can be used in the FSE field. The most used tool among the 35 identified articles was the SD-modeling (19 studies), followed by the CLD (12 studies), the STS (11 studies), and finally SAs (2 studies). Fourteen of the studies explicitly presented the used equations for the development of their models, and 20 of the studies performed simulations.

4.2 Application and Discussion of the ST Theory To the FSE Field (Stage 3)

Stage 3 of the literature review examines the identified papers for their application of ST. Three aspects are considered: (1) reported case studies; (2) STS application, and (3) SAs for capturing FSE principles.

4.2.1 Case Studies Applying ST Theory To the FSE Field

The case studies consider the application of STS and SAs in fire safety and building regulation. Meacham et al. [90] and Meacham and van Straalen [89] proposed a risk-informed, performance-based approach integrating acceptable risk levels and performance expectations within regulatory systems, recognizing complex stakeholder interactions. Meacham [21] emphasized treating fire safety as an emergent property of infrastructure. Frantzich et al. [38] introduced the SAFR-B framework using risk indexing and decision-support tools to balance sustainability and fire resilience. STS and ST principles were also applied to tunnel fire safety management (TFSM), integrating risk management, feedback loops, and adaptive decision-making. Furthermore, two studies explored the use of SAs in safety engineering, proposing eight SAs that could be adapted for FSE [58, 59]. Overall, these studies demonstrate the potential of the ST approach in advancing fire safety regulation through interdisciplinary, systems-based thinking.

4.2.2 Socio-technical Systems Applications

Performance-based building codes encourage innovation but face skepticism due to goals and requirements that are deemed unclear, and insufficient data, tools, and methods to meet safety expectations [90]. To address these challenges, Meacham et al. [90] and Meacham and van Straalen [89] proposed a risk-informed, performance-based approach integrating acceptable risk levels, performance expectations, and design criteria within the regula-

Table 4 Retained studies considering the SD application included in this literature review

Code/title	Source	Type of source	Year	References
-I- System Dynamics analysis for petrochemical enterprise fire safety system.	Procedia Engineering	Conference paper	2018	[67]
-II- Probability prediction and cost-benefit analysis based on SD.	Process Safety and Environmental Protection	Journal paper	2018	[68]
-III- Study on evacuation behavior of urban underground complex in Fire Emergency based on SD.	Sustainability	Journal paper	2022	[7]
-IV- Dynamic simulation of the group behavior under fire accidents based on SD.	Procedia Engineering	Conference paper	2018	[69]
-V- Subway fire cause analysis model based on SD: a preliminary model framework.	Procedia Engineering	Journal paper	2016	[70]
-VI- A system thinking approach for evacuation during fire incidents considering SD.	IEEE	Conference paper	2022	[6]
-VII- The research of high-rise building fire safety simulation model based on SD.	Applied Mechanics and Materials	Journal paper	2014	[71]
-VIII- A simulation model for studying the implementation of performance-based fire safety design in buildings.	Automation in Construction	Journal paper	2008	[72]
-IX- A study of the use of a performance-based approach to fire safety design in buildings.	Structural Survey	Journal paper	2008	[73]
-X- Using System Dynamics for Cost-Benefit Analysis of fire safety engineering features.	ESFSS 2024 Conference	Poster	2024	[74]
-XI- Impact of Technical, Human, and Organizational Risks on Reliability of Fire Safety Systems in High-Rise Residential Buildings—Applications of an Integrated Probabilistic Risk Assessment Model.	Applied Sciences	Journal paper	2020	[75]
-XII- Sensitivity and Uncertainty Analyses of Human and Organizational Risks in Fire Safety Systems for High-Rise Residential Buildings with Probabilistic T-H-O-Risk Methodology.	Applied Sciences	Journal paper	2021	[76]
-XIII- Applying systems thinking concepts in the analysis of major incidents and safety culture.	Safety Science	Journal paper	2010	[77]
-XIV- Incorporation of technical, human, and organizational risks in a dynamic probabilistic fire risk model for high-rise residential buildings.	Fire and Materials	Journal paper	2021	[78]
-XV- Lessons learned from critical accidental fires in tunnels.	Tunnelling and Underground Space Technology	Journal paper	2021	[79]
-XVI- Blowout fire probability prediction of offshore drilling platform based on system dynamics.	Journal of Loss Prevention in the Process Industries	Journal paper	2019	[80]
-XVII- Developing safety archetypes of the construction industry at the project level using SD.	Journal of Safety Research	Journal paper	2018	[58]
-XVIII- Identifying safety archetypes of construction workers using SD and content analysis.	Safety Science	Journal paper	2020	[59]
-XIX- System dynamics research of non-adaptive evacuation psychology in toxic gas leakage emergencies of chemical park.	Journal of Loss Prevention in the Process Industries	Journal paper	2021	[81]
-XX- Sustainable building materials assessment and selection using system dynamics.	Journal of Building Engineering	Journal paper	2021	[82]

Table 4 (continued)

Code/title	Source	Type of source	Year	References
-XXI- Modelling of safety performance in building construction projects using system dynamics approach in Tanzania.	Safety	Journal paper	2024	[83]
-XXII- Risk analysis and simulation of large bridge construction based on system dynamics.	Buildings	Journal paper	2024	[84]
-XXIII- A system dynamics-based environmental benefit assessment model of construction waste reduction management at the design and construction stages.	Journal of Cleaner Production	Journal paper	2018	[64]
-XXIV- Use of system dynamics as a decision-making tool in building design and operation.	Building and Environment	Journal paper	2010	[85]

Table 5 Relevant studies related to the STS application included in this literature review

Code/title	Source	Type of source	Year	References
-XXV- Decision Support Framework for Sustainable and Fire Resilient Buildings (SAFR-B).	Fire Technology	Journal paper	2024	[38]
-XXVI- Tunnel fire safety management and systems thinking: Adapting engineering practice through regulations and education.	Fire Safety Journal	Journal paper	2024	[86]
-XXVII- Conceptual Basis for a Sustainable and Fire Resilient Built Environment.	Fire Technology	Journal paper	2023	[37]
-XXVIII- Risk and Performance Assessment Framework for a Sustainable and Fire Resilient Building Environment (SAFR-BE).	Society of Fire Protection Engineers Foundation	Report	2023	[39]
-XXIX- Fire safety of existing residential buildings: Building regulatory system gaps and needs.	Fire Safety Journal	Journal paper	2023	[48]
-XXX- Sustainable and Fire Resilient Built Environment (SAFR-BE).	Springer International Publishing	Chapter	2023	[87]
-XXXI- Toward a Sociotechnical Systems Framing for Performance-Based Design for Fire Safety.	Springer International Publishing	Chapter	2022	[51]
-XXXII- A Sociotechnical Systems Framework for Performance-Based Design for Fire Safety.	Fire Technology	Journal paper	2022	[21]
-XXXIII- A holistic framework for development and assessment of risk-informed performance-based building regulation.	Fire and Materials	Journal paper	2021	[88]
-XXXIV- A socio-technical system framework for risk-informed performance-based building regulation.	Building Research & Information	Journal paper	2018	[89]
-XXXV- Risk-informed performance-based approach to building regulation.	Journal of Risk Research	Journal paper	2010	[90]

tory system, viewing it as an STS that considers legal, regulatory, and market interactions. Meacham [21] further emphasized treating fire safety as an emergent property of infrastructure, identifying key system attributes that can be controlled during design to reduce long-term uncertainties. This aligns with SAs in ST, such as “Fixes That Fail,” where short-term compliance can create long-term vulnerabilities, and “Shifting the Burden,” where prescriptive rules hinder adaptive, risk-informed decision-making. Frantzich et al. [38] contributed by introducing the Sustainable and Fire Resilient Buildings (SAFR-B) frame-

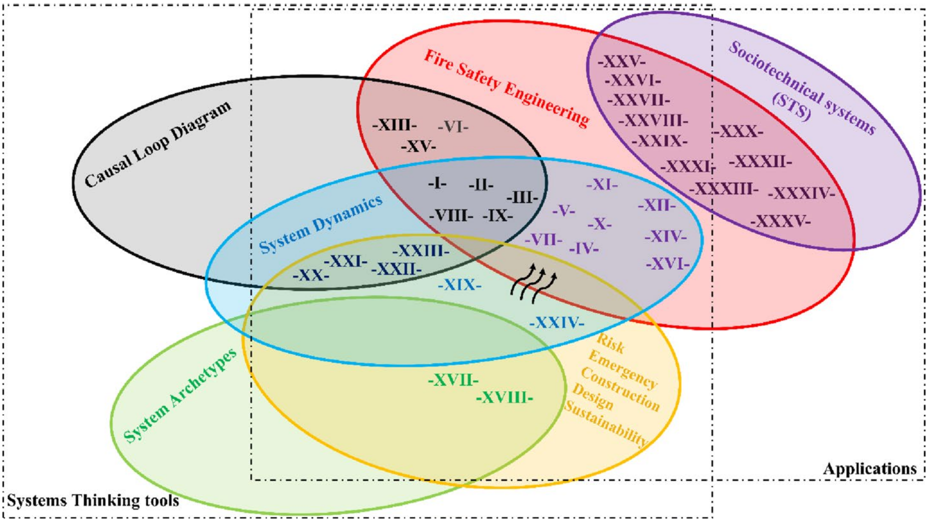


Fig. 4 Clustering the retained research studies according to the applied Systems Thinking approach

work, which applies risk indexing and analytical hierarchy processes to balance sustainability and fire resilience, leveraging ST tools like CLDs to map feedback mechanisms. The broader application of STS and ST principles in fire safety has been explored by Meacham & McNamee [87], as well as studies on Sustainable and Fire Resilient Built Environments (SAFR-BE) [37, 39]. By incorporating whole-of-life, multi-agency, and holistic regulatory considerations, as explored by Meacham [48], these frameworks advance the understanding of regulatory evolution and the necessary conditions for widespread acceptance of PBD in fire safety.

More recently, STS and ST concepts have been applied to TFSM. This approach integrates risk management and FSE with prescriptive and experience-based solutions while incorporating ST to evaluate the system as a whole. By viewing TFSM as an interconnected system, the study highlights the role of feedback loops, stakeholder interactions, and adaptive decision-making in enhancing safety and efficiency. Furthermore, regulatory adaptation, interdisciplinary collaboration, and improved education programs have been identified as essential enablers of this systems-based approach [86].

Hence, integrating STS and ST approaches—including CLDs, SD modeling, and SAs—can provide a structured methodology for addressing the complexities of performance-based building regulation and fire safety. Recognizing the interdependencies among stakeholders, regulatory frameworks, and technological advancements enables a more resilient and adaptive approach to building safety. The progression of these frameworks, from Meacham's early work on PBD for fire safety to recent studies on SAFR-BE and TFSM, illustrates the growing attention to interdisciplinary, systems-based thinking in managing fire risk and sustainability challenges within the built environment.

4.2.3 Using System Archetypes for Capturing Fire Safety Engineering Principles

In this section, SAs as part of the ST theory, are discussed and compared. Two studies have been identified in this literature review that explore the use of SAs for purposes within the scope of this review: (1) interactions among safety, accident causation, and human factors [58], and (2) interdependencies among accident investigation, workers, and productivity [59].

In total eight SAs were proposed between these two studies [58, 59], in each article the SAs were comprehensively discussed considering dynamic complexity, behavior over time, and leverage points in order to provide guidance on how to deal with the archetype. These archetypes were applied to the construction industry, but they can be adapted to the FSE field. The direct application of SAs to FSE has not been explored yet. Therefore, potential applications based on the architecture of the SAs, and on how they have been applied previously, are shown in Table 6. These are the same SAs which were introduced in Table 1; Fig. 1. For more information, see the text in Sect. 2.3.

For instance, the "Limits to Success" archetype can be applied to fire safety regulations where resource constraints, such as budgets or system capacity, hinder continuous improvement. Addressing these constraints requires a systems-level approach that aligns with the STS framework proposed by Meacham [21, 89], ensuring that regulatory and market environments do not impose barriers to progress. The "Shifting the Burden" archetype is evident in the reliance on prescriptive fire safety measures rather than investing in long-term adaptive solutions, an issue also highlighted in SAFR-B frameworks [37, 38]. Similarly, the "Eroding Goals" archetype reflects the tendency to lower safety standards under cost or time pressures, reinforcing the need for robust performance-based approaches that integrate risk-informed decision-making. Moreover, the "Tragedy of the Commons" archetype underscores the importance of collective responsibility in shared fire safety environments, such as multi-use buildings or community-level infrastructure. This aligns with Meacham's [48] work on whole-of-life regulatory approaches and multi-agency collaboration, demonstrating how systemic interdependencies influence fire safety resilience.

4.3 Application and Discussion of SD Modeling To the FSE Field (Stages 4–5)

In stages 4–5 of the adopted research framework current SD applications are investigated and possible ST applications in FSE are presented. Different subsections are introduced, increasing the level of complexity linked to each SD-related tool: from the adoption and development of feedback loops to their integration in CLDs and SD-based models. First, Sect. 4.3.1 explains the relevance of each of the identified 24 studies. Then, in Sect. 4.3.2,

Table 6 Potential uses for the FSE field

System Archetype	Potential uses for the Fire Safety Engineering field
Limits to success	Identify and address constraints (e.g., resources, budgets, system capacity) that limit improvements in fire safety
Shifting the burden	Avoid over-reliance on quick fixes and prioritize fundamental solutions (e.g., long-term investments in infrastructure or training)
Eroding goals	Maintain high safety standards and resist pressures to lower goals, especially in the face of cost or time constraints
Tragedy of the commons	Promote collective responsibility for fire safety in shared systems and environments to prevent resource depletion or underperformance

the main feedback loops are described. In Sect. 4.3.3 a CLD from the literature is explained in detail. Finally, Sect. 4.3.4 presents the observed implications of SD-modeling for the FSE field.

Additionally, possible new applications are proposed taking into account the following research categories identified from the SFPE Handbook and the ESFSS 2024 Conference: (1) Fluid mechanics and fire dynamics [91–95]; (2) Structural fire engineering [96, 97]; (3) Fire scenarios and performance-based design (PBD) [98, 99]; (4) Fire detection and suppression systems [3, 47, 100–107]; (5) Human behavior and egress design [11, 108–112]; (6) Risk Analysis and decision-making [113–118]; and (7) Sustainability [119].

4.3.1 Case Studies that Applied an SD-Related Tool To the FSE Field

Table 7 shows the aim of each research article included in *Stage 4*, as well as a short description of the study.

The main software used is Vensim, while the database adopted strongly depends on the aim of each research. Some other methods have been combined with an ST approach to support a holistic evaluation, such as the Analytical Hierarchy Process (AHP), ground theory method (GTM), Fishbone diagram, and Cost-benefit analysis (CBA). A recent trend considers combining Bayesian Networks (BN) with SD modeling [75, 76, 78]. This approach has several advantages for FSE [75, 76, 78]. Table 8 shows examples from the literature of combining ST tools with non-ST methods. The most common research category is *Risk analysis and decision-making*, which is aligned with one of the major advantages of using an ST-tool.

4.3.2 Main Feedback Loops for Studying the Interactions Linked To the FSE Field

Table 9 presents the feedback loops (FLs) identified through the literature review most relevant for the FSE field. These loops highlight interdependencies in FSE, particularly in high-risk environments like petrochemical enterprises and tunnel systems. The FLs can be categorized into reinforcing loops (RLs), which amplify certain behaviors, and balancing loops (BLs), which stabilize systems.

For example, FL01-04 highlights that investment in fire safety within petrochemical enterprises plays a crucial role in enhancing staff training, fire safety management, and technological advancements. These improvements create a reinforcing cycle, increasing overall fire safety and efficiency. Similarly, performance-based approaches in FSE influence administrative processes, shaping regulatory frameworks and professional awareness (FL05-06).

A key example in tunnel fire safety is the balance between safety responses and infrastructure investments. FLs 7–10 illustrate the dynamic interactions between fire risk, safety measures, and traffic regulations in tunnels. The balancing loops (B1, B2, B3) work to control fire hazards: restrictions on vehicle types and cargo (B1) reduce traffic volume and vehicle-related problems, lowering fire incidents and eventually easing restrictions; heightened fire risks (B2) increase fire severity, prompting stronger engagement from self-defense fire brigades, which mitigates risk; and severe fires (B3) drive local fire squads to act, containing fire spread and enhancing tunnel safety. In contrast, the reinforcing loop (R1) presents a challenge—more vehicle ignitions lead to increased investments in tunnel protection, which relaxes vehicle restrictions, raises traffic volume, and ultimately results in more ignitions.

This feedback loop-based analysis underscores the critical role of coordinated safety efforts, technological improvements, and infrastructure investment in minimizing fire risks. Efficient management of balancing loops ensures system stability, while reinforcing loops, when harnessed effectively, promote continuous improvement in fire safety.

4.3.3 Causal Loop Diagrams Built for Fire Safety Engineering

CLDs aim to capture and visualize the complex interdependencies among different influencing factors. A CLD is built considering the integration of different FLs, so the ultimate dynamic behavior is controlled by the force and number of BLs and RLs that compose the system. CLDs capture the complexity of a given system by visualizing their intrinsic interdependencies. This has a huge advantage in the FSE field because FSE needs to move beyond static risk assessment approaches by adopting dynamic models that account for the interrelations among different safety features.

To demonstrate the concept, a CLD is chosen from the literature [67] which models the interrelations linked to the safety level and fire safety investment in a petrochemical enterprise (Fig. 5). This CLD contains four RLs (previously explained in Table 9- FLs 01–04). The expected behavior of this system is exponential growth or decline. Also, the presence of multiple RLs can increase the nonlinearity and instability. At the core of the diagram is the role of financial investment in fire safety, which cascades into various subsystems.

The CLD suggests four critical pathways through which investments enhance fire safety: staff training, facility purchases, safety management, and technical improvements. These factors collectively contribute to an increased safety level. According to [67], a higher safety level fosters a greater commitment to ongoing fire safety improvements, which, in turn, encourages further investment in fire safety measures. Thus, four reinforcing loops are formed. The reinforcing nature of all four loops creates a virtuous cycle, where increased investment leads to enhanced safety measures, better-trained personnel, more advanced equipment, and higher managerial efficiency, culminating in a safer chemical industry park and even higher fire safety investments. Positive feedback loops are critical in ensuring that small gains in safety performance drive further investments, creating sustained improvement over time. This CLD can serve as a basis for developing more realistic models in the FSE field, specifically aligned with the research categories of *Risk analysis and decision-making*, and *Sustainability*.

More complex CLD models have been developed in previous studies. For instance, a CLD for modeling the complex interdependencies linked to the occurrence and prevention of a blowout fire is introduced in [68], considering event probabilities, safety measures, and dynamic relationships. Aligned with the research category *Human behavior and egress design*, a CLD for representing mass crowd evacuation behavior during an emergency is proposed in [7]. A CLD was built for the building approval system in Hong Kong [72, 73], to represent the interrelations between the proposal, approval, and application of performance-based fire designs. Other identified CLDs that can be helpful for FSE are related to sustainable building materials assessment and selection [82], safety performance in building construction projects [83], environmental benefits assessment [64], and risk evolution of large bridge construction [84].

Table 7 Relevant information for each selected research Article (Stage 4)

Code	Aim	General description	Methods/tools	Database/source of info./software	Relevance for FSE (research category)
-I-	Study the fire safety dynamics linked to an oil tank storage area	Fire safety level considers the following four main parameters: (1) personnel awareness level, (2) fire safety management level, (3) level of fire fighting facilities, (4) technological level	CLD, SD	Case study: Chemical plant in Nanjing Liuhe Chemical Industrial Park in Nanjing, Jiangsu province. Vensim	Risk Analysis and decision making
-II-	Dynamic probability prediction, and cost-benefit analysis	A new method for evaluating blowout fire prevention and control measures is introduced considering a cost-benefit analysis Firstly, a dynamic probability prediction model for blowout fire is introduced using SD. Secondly, a cost-benefit analysis of the corresponding safety measures is carried out using SD simulation. Thirdly, case studies of blowout fire probability prediction and the cost-benefit analysis of safety investments are demonstrated for some offshore drilling platforms	CLD, SD, CBA	Probability database (fire safety handbook) Vensim	Fire scenarios and PBD Risk Analysis and decision making
-III-	Study large-scale evacuation behavior of urban underground complexes with limited evacuation routes and egress during a fire	The model captures the typical phenomenon of group evacuation behaviors under seven operating situations with different total initial occupant numbers	Fishbone diagram, CLD, SD, Evacuation simulation software, Case analysis	Previously developed research Vensim	Human behavior and egress design Fire detection and suppression systems
-IV-	Study the group behavior under severe fire accidents in chemical industrial parks	A model of the group behavior was developed based on the epidemic model and an SD theory and method	Epidemic model (the SIR model), SD	Vensim	Human behavior and egress design
-V-	Study the main influencing factors on the occurrence, spread, and controlling of subway fires	This research collects major subway fire cases in nearly 20 years. The causes of the fire accidents are assessed. The influencing factors are extracted including equipment, human, environmental, and emergency management factors	Statistics, and SD	Reports on the proportion of different inducing factors related to subway accidents in China and abroad Vensim	Fluid mechanics and fire dynamics Risk Analysis and decision making

Table 7 (continued)

Code	Aim	General description	Methods/tools	Database/source of info./software	Relevance for FSE (research category)
-VI-	Analyze the evacuation of buildings during a fire	This research develops a Systems Thinking framework for the evacuation of buildings during a fire. The methodology includes the fire evacuation process as a whole considering different factors affecting the evacuation process	Feedback loops, CLD	Feedback loops	Human behavior and egress design Risk Analysis and decision making
-VII-	Study the factors affecting high-rise building fire safety considering staff awareness, fire design, fire-fighting facilities, daily management, and technology	The model was applied to a high-rise building	SD	Vensim	Structural fire engineering Fire detection and suppression systems Risk analysis and decision-making
-VIII-	Examine the effect of introducing a performance-based approach in the regulatory system by using a conceptual system dynamic model	The model is conceptualized around the technical and mental factors that impact the decisions of building control officials and various challenges regarding the Hong Kong building control system	CLD + SD	Hong Kong specifics Vensim	Fire scenarios and PBD
-IX-	Compare the use of performance-based fire safety design in different locations by using SD modeling	This paper shows a brief comparison of the use of performance-based fire safety design in three locations and presents the use of an SD model to examine how technological investment influences the use of performance-based fire safety design	CLD + SD	Hong Kong specifics Vensim	Fire scenarios and PBD
-X-	Show how SD models can be used for the CBA of fire safety features for buildings. The CBA corresponds with an ALARP evaluation whereby the Life Quality Index (LQI) is adopted for the evaluation of risk to life	Three case studies are adapted from existing literature: (1) sprinklers in Australian single-family residences, (2) sprinkler requirements considering different sprinkler classes, and (3) door width requirements for retail spaces	SD	Data reported from the fire-specialized literature Vensim	Risk analysis and decision-making Sustainability

Table 7 (continued)

Code	Aim	General description	Methods/tools	Database/source of info./software	Relevance for FSE (research category)
-XI-	Application of an alternative probabilistic risk assessment methodology known as T-H-O-Risk, which integrates technical, human, and organizational risks using Bayesian network (BN) and SD modeling	The approach is demonstrated through seven case studies involving the design of high-rise residential buildings. By adopting an incremental risk assessment framework, the study quantifies the effects of human and organizational errors (HOEs) on various fire safety systems, including sprinklers, occupant warning systems, smoke detectors, and smoke control systems	BN + SD	Data collection. Fire statistics. HOEs data Vensim	Risk analysis and decision-making Fire scenarios and PBD Fire detection and suppression systems
-XII-	This study adopts the technical-human-organizational risk (T-H-O-Risk) methodology to fill critical knowledge gaps in probabilistic risk analysis (PRA) for high-rise residential buildings	Develop an Enhanced PRA Methodology: Address limitations in deterministic fire engineering methods, which tend to significantly underestimate safety levels, leading to inaccurate fire risk assessments Improve Fire Safety Verification: Integrate probabilistic risk analysis and HOEs to provide a more comprehensive risk perspective and overcome the deterministic nature of current verification practices Conduct Sensitivity and Uncertainty Analyses: Address uncertainties in numerical estimates used in fault trees, event trees, Bayesian networks, and system dynamics, and assess their propagation within probabilistic models Quantify Human and Organizational Risks: Provide insights that support a policy shift toward a sustainable, risk-based regulatory framework for high-rise residential buildings	BN + SD Event Tree	Data obtained from the literature for high-rise building fires Vensim	Risk analysis and decision-making Fire scenarios and PBD Human behavior and egress design
-XIII-	Enhancing traditional causal analysis tools by integrating systems thinking methodologies	The paper illustrates an ST approach through a case study of the Bellevue hazardous waste fire in Western Australia. The analysis reveals how various actors, responding to individual pressures, collectively fostered a poor safety culture that significantly contributed to the 2001 fire	CLD	Feedback loops	Risk analysis and decision-making

Table 7 (continued)

Code	Aim	General description	Methods/tools	Database/source of info./software	Relevance for FSE (research category)
-XIV-	This paper introduces a comprehensive technical-human-organizational risk (T-H-O-Risk) methodology to enhance PRA by integrating human and organizational risks	Three case studies involving structures ranging from 18 to 24 storeys demonstrate the approach. Societal risks are visualized through F-N curves. Findings reveal that fire safety designs neglecting HOEs typically underestimate risks by around 20% and, in extreme cases, up to 42%. Additionally, HOE-related risks can fluctuate by up to 30% over a 10-year period. Sensitivity analyses highlight the significant impact of factors such as inadequate training, poor safety culture, and ineffective emergency plans on overall risk	BN + SD Event tree	Data collection. Fire statistics. HOEs data	Risk analysis and decision-making Human behavior and egress design Structural fire engineering
-XV-	To review literature on historical tunnel accidents and map the common timeline of tunnel fire events	Key findings: (1) Complex Causes and Greater Damage: Tunnel fires are far more complex and destructive than other types of fires; (2) Dynamic and Interconnected Systems: These incidents involve numerous continuous and dynamic causal relationships, including interactions among vehicle systems, tunnel control mechanisms, and safety responses; (3) Critical Mental Models: Two mental models emerged as vital for enhancing safety: (a) "The experience of tunnel control center operators is as crucial as the safety response itself" and (b) "Safety should take precedence over traffic volume in tunnel operations."	CLD	Data on critical accidental fires in tunnels that occurred between 1949 and 2016 Vensim	Risk analysis and decision-making Structural fire engineering
-XVI-	A dynamic probability prediction model is introduced by integrating the fault tree with a system dynamics model	The model is applied to predict the dynamic probability of blowout fires in offshore drilling operations. Additionally, sensitivity analyses using mutual information are conducted to identify key contributory factors to blowout fires The research provides safety managers with reliable and practical risk control strategies to help prevent future accidents	Fault Tree + SD	Probability database (fire safety handbook) Vensim	Risk analysis and decision-making. Fire scenarios and PBD
-XVII-	This research aims to detect and categorize behavior patterns recurring in construction safety management	Four archetypes were identified. These archetypes take into account the following variables (i) delay in design, (ii) number of subcontractors, (iii) cost of the project, and (iv) safety. Each archetype is discussed at different steps of dynamic complexity, behavior over time, and the leverage point to show how to deal with the archetype	System Archetypes, Content analysis, and Ground Theory Method (GTM)	Systems Archetypes structure Vensim	Risk analysis and decision-making

Table 7 (continued)

Code	Aim	General description	Methods/tools	Database/source of info./software	Relevance for FSE (research category)
-XVIII-	To better understand the dynamic complexity of construction safety by identifying behavioral patterns of workers that recur in construction projects	Construction project management implies a complex effort due to the unique, dynamic, and temporary nature of construction projects. Moreover, there is a gap in exploring the systematic patterns responsible for the occurrence of accidents. 100 papers were reviewed and 20 interviews were conducted	Content analysis and ground theory method (GTM), System Archetypes (SAs)	The databases included the Scopus database, Taylor & Francis Online, and American Society of Civil Engineers (ASCE) library. They were searched using keywords such as "accident" and "construction. Vensim	Risk analysis and decision-making
-XIX-	An SD model for people's behavior is developed considering the disaster environment and the evolution of crowd motion	Simulation experiments were carried out for different disaster severity, visibility, and occupant groups	SD	A major toxic gas leakage accident in a chemical plant is used as an example Anylogic	Human behavior and egress design
-XX-	This paper proposes an SD-based model for simulating parameter interactions for selecting sustainable building materials	The parameters that affect the selection of sustainable building materials are derived from rating systems, previous studies, and expert criteria. A case study to appreciate the performance of common building materials is presented to prove the main characteristics of the suggested model	Questionnaire survey, CLD, SD, Analytical Hierarchy Process (AHP)	A case study to consider the performance of common building materials like wood, concrete, and steel is presented Vensim	Sustainability Structural fire engineering
-XXI-	Develop an SD model to study the influencing factors on safety performance in building construction projects	Identification of key variables using factor reduction; 19 factors out of 143 variables from a questionnaire were found to be key factors	CLD + SD	255 building construction projects in five zones of Tanzania Stella	Structural fire engineering Risk analysis and decision-making

Table 7 (continued)

Code	Aim	General description	Methods/tools	Database/source of info./software	Relevance for FSE (research category)
-XXII-	Study the interaction mechanisms and dynamic changes during the construction of large bridges	A CLD and an SD model are proposed. As a case study, a large bridge construction project is considered	CLD + SD	Case study large bridge construction Vensim	Structural fire engineering Risk analysis and decision-making
-XXIII-	Build a two-stage environmental benefit assessment based on SD modeling which includes construction waste reduction management, waste generation, and environmental benefits	The simulation results demonstrate that the dynamic model assessed the environmental benefit of construction waste reduction effectively at the design and construction stage	CLD + SD	Case study construction waste reduction management at the design and construction stages Vensim	Sustainability
-XXIV-	Develop a decision-making tool based on SD for building design and operation	A method is discussed to link a building information model (BIM) of the building with an SD model to enable the automated capture of relevant building features in the SD model	SD	Historic uses within civil and environmental engineering Stella	Risk analysis and decision-making

Table 8 Examples of combining systems thinking (ST) tools with non-ST methods in the reviewed literature

ST tool(s)	Non-ST Tool(s) combined	Capability of ST tool(s) explored in the reference	Typical role of the non-ST tool(s)	Reference(s)
System Dynamics (SD)	Cost-Benefit Analysis (CBA)	Simulates system dynamics over time; evaluates intervention impacts	Quantifies costs and benefits; assesses economic feasibility	Wang et al. [68]
Causal Loop Diagram (CLD) + SD	Probabilistic Risk Assessment (PRA)	Maps feedback loops and interactions influencing risk	Quantifies probabilities and consequences of failure scenarios	Tan et al. [75, 76]
CLD	Bayesian Networks (BN)	Identifies system structure and causal pathways	Calculates conditional probabilities and supports probabilistic reasoning	Tan et al. [78]
SD	Event Tree Analysis	Models time-dependent changes in safety system performance	Structures possible event sequences from initiating events	Tan et al. [76]
SD	Fault Tree Analysis	Simulates dynamic effects of component failures	Models logical combinations of failures leading to system-level events	Wang et al. [80]
SD	Analytical Hierarchy Process (AHP)	Tests dynamic impacts of parameter choices over time	Weighs decision criteria and ranks alternatives	Sahlol et al. [82]

Overall, by applying the CLD principles fire safety engineers can better anticipate risks, implement more effective safety measures, and ultimately enhance the system safety. Although CLDs can offer a clear representation of complex system safety, they do not provide quantitative input for decision-making. To address this issue, CLDs can be further translated into SD models, and by performing simulations for different scenarios, the decision-making process can be improved.

4.3.4 System Dynamics Models for Fire Safety Engineering

Despite the several advantages offered by the development of CLDs, these are often adopted as a qualitative tool; so it is necessary sometimes to transform the CLD into a Forrester-diagram (or SD-based) model for quantifying key variables and support efficient decision-making. This section focuses on explaining the main advantages of SD-based models developed and applied in the FSE field, or that can be used for specific purposes linked to FSE.

In this section, an SD model is chosen from the literature [68] to illustrate the concept. The SD model has been created to perform a cost-benefit analysis for an offshore platform considering investments in safety management and safety education, the probability of a blowout fire, the total accident loss, the safety management costs, the total demand for safety management, and the number of employees (Fig. 6).

This SD model illustrates a complex interplay between various factors influencing safety management, accident risks, and costs associated with fire safety. Investments in safety management directly impact the probability of accidents and fires by addressing unsafe behaviors and equipment conditions. Safety education investment improves employee training and the proportion of skilled employees, reducing the likelihood of unsafe actions. Additionally, the diagram outlines the economic consequences of accidents, including direct costs (e.g., damages and compensation) and indirect costs (e.g., production downtime and

Table 9 Some feedback loops (FLs) developed for the FSE field

No	Feedback loop	Meaning	Code (Table 7)
01	RL (A)- petrochemical enterprises fire safety investment→ + staff training → + personnel fire training level→ + safety level of petrochemical enterprises→+ firefighting efficiency→ + fire safety improvement→ + petrochemical enterprises fire safety investment	According to this feedback loop, investments in fire safety for petrochemical plants induce a positive feedback effect through their effects on staff training, firefighting efficiency, and fire safety improvement	-I-
02	RL (B): petrochemical enterprises fire safety investment → + fire facilities purchase → + fire service level → + safety level of petrochemical enterprises → + firefighting efficiency → + fire safety improvement→ + petrochemical enterprises fire safety investment	According to this feedback loop, investments in fire safety for petrochemical plants induce a positive feedback effect through their effects on the available fire fighting facilities	-I-
03	RL (C): petrochemical enterprises fire safety investment → + fire safety management → + fire safety management level → + safety level of petrochemical enterprises →+ firefighting efficiency → + fire safety improvement→ + petrochemical enterprises fire safety investment	According to this feedback loop, investments in fire safety for petrochemical plants induce a positive feedback effect through their effects on safety management, firefighting efficiency, and fire safety improvement	-I-
04	RL (D): petrochemical enterprises fire safety investment → + technical improvement → + the technical level → + safety level of petrochemical enterprises → + firefighting efficiency → + fire safety improvement → + petrochemical enterprises fire safety investment	According to this feedback loop, investments in fire safety for petrochemical plants induce a positive feedback effect through their effects on the technical improvement, firefighting efficiency, and fire safety improvement	-I-
05	RL2- No. of projects using FSE approach → + No. of FSE applications submitted to Fire Safety Committee (FSC) → + No. of approved FSE applications → + Awareness of building professionals → + Rate of using performance-based approach in buildings design → + No. of projects using FSE approach	Self-strengthening effect of the number of projects using an FSE approach because of its impact on the number of applications submitted and approved, the awareness of building professionals, and the rate of using a performance-based approach in building design	-VIII-
06	BL3- No. of FSE applications submitted to FSC → + Workload pressure of building authorities → - Passing rate of FSE applications → + No. of approved FSE applications → + Technological level → + Rate of using performance-base approach in buildings design → + No. of using FSE building applications	According to this feedback loop, the number of FSE applications submitted to FSC induces a negative feedback effect (balancing) through their effects on the workload pressure of building authorities, the technological level, and the rate of using PBD in buildings	-IX-
07	B1 (Limited Vehicle Use Loop): Limit to Vehicle Types and Carried Goods → - Traffic volume → + Vehicle Problem Rates → + Limit to Vehicle Types and Carried Goods	When severe vehicle-related issues arise, authorities impose restrictions on vehicle types and cargo. This decreases tunnel traffic volume, which in turn reduces the frequency of vehicle problems, leading to fewer fires. This eventually results in less stringent restrictions	-XV-
08	B2 (Self-Defense Fire Brigade Commitment to Safety Response): High Risks → + Fire Severity → + Self-defense Fire Brigade Commitment to Safety Response → - High Risks	High risks increase the severity of fires. This leads to greater engagement from self-defense fire brigades, ultimately reducing risks	-XV-

Table 9 (continued)

No	Feedback loop	Meaning	Code (Table 7)
09	B3 (Tunnel Damage Containment Loop): Fire Severity→ + Local fire squad commitment to safety response → - Unsafe Conditions → + Fire Severity	The possibility of severe fires leads to more local fire squads' efforts in fire suppression, which help contain fires and prevent them from spreading, improving overall tunnel safety	-XV-
10	R1 (Tunnel Protection Investment Loop): Vehicle Ignition → + Tunnel Protective Investment → - Limits on vehicles → - Traffic volume → + Vehicle Problem Rates → + Vehicle Unsafe Conditions → + Vehicle Ignition	An increase in vehicle ignitions leads to greater investment in tunnel protection, which relaxes vehicle restrictions, resulting in higher traffic volume and, consequently, more ignitions	-XV-

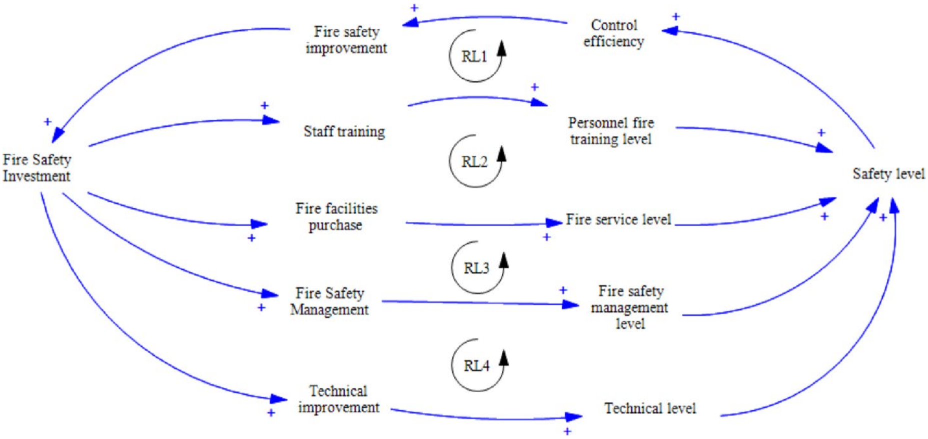


Fig. 5 CLD for modeling the interrelations linked to the safety level and fire safety investment. Adapted from [67]

reputation loss). These are aggregated into total accident loss, which feeds back into the benefit of enhanced safety measures.

The model also considers human resource dynamics. Employee turnover, training, and skill growth are central to maintaining a safe working environment. Resignation rates (linked to stress, unsafe conditions, or fire incidents) affect the number of new employees and their proportional representation in the workforce. New employees often require more intensive training, adding to safety education costs. Training strength, influenced by safety education investment, increases the safety skill level of employees, thus reducing accidents.

The model highlights feedback loops where improved safety management and education investments enhance overall safety performance. This leads to fewer accidents, reducing both economic losses and the need for reactive investments, thus strengthening the investment in improved safety management and education.

Safety costs per person per hour, total safety management investment, and associated increased costs—such as salaries of safety officers and training expenses—create a balancing feedback loop between investment adequacy and organizational budget constraints. Increased safety investments must be justified by measurable improvements in safety per-

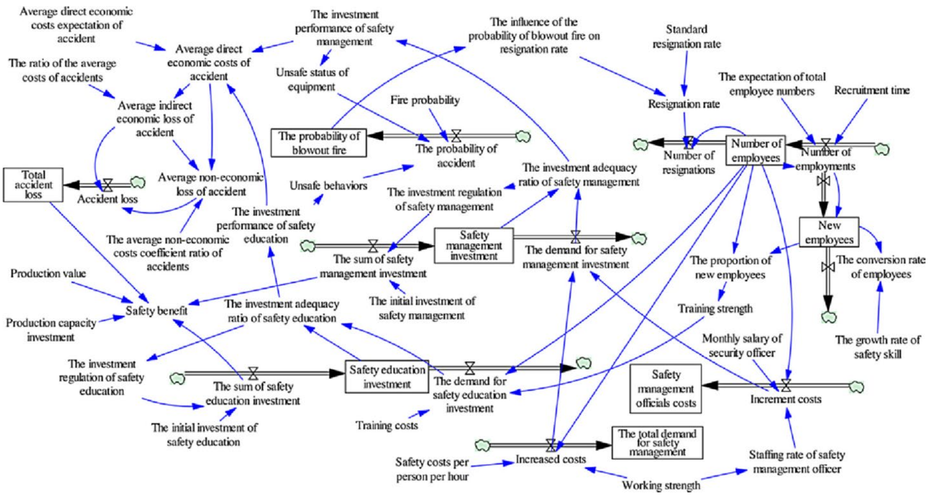


Fig. 6 SD for performing a Cost-benefit analysis [68]. Reproduced with permission from Elsevier Ltd

formance and corresponding reductions in accident-related losses. As safety management effectiveness reduces accident risks and associated costs, it reinforces the rationale for continued investment. However, rising costs place financial pressure on budgets, limiting the extent of future investments. This balancing mechanism, as shown in the SD model [68], results in a cap on the practically achievable level of safety.

Other SD models have been applied in the FSE. For example, an SD model was developed for studying evacuation planning considering exit evacuation capacity and guidelines [7]. Complementing a previous CLD, an SD model for the building approval system in Hong Kong considering the proposal, submission, and approval of building design projects has been established [72, 73]. Additionally, an SD model for the safety performance in building construction projects considering accident frequency, and associated costs was developed [83]. To compute the fire safety level of high-rise buildings considering the fire fighting efficiency and fire protection benefits, an SD model has been built [71]. Recent studies have coupled SD modeling with Bayesian modeling and Event trees for probabilistic risk assessments [75, 76, 78]. This new Technical-Human-Organizational-Risk (T-H-O-Risk) methodology offers an interesting approach to addressing FSE challenges. Despite SD modeling being only a stage in this methodology, it offers dynamic risk profiles [78]. This approach has been applied to high-rise residential buildings [75, 78].

Although these studies highlight the potential of SD in FSE, additional case studies and real-world applications are necessary to validate these models and enhance their accuracy and effectiveness. Practical implementations would help identify potential gaps, refine assumptions, and improve the reliability of SD-based approaches in predicting fire risks and optimizing safety measures. Integrating empirical data from real fire incidents and safety interventions would strengthen model calibration, ensuring that SD applications in FSE reflect the complexities of fire dynamics, human behavior, and regulatory constraints. Expanding case studies and practical applications will ultimately bridge the gap between theoretical advancements and their real-world utility, fostering a more robust and data-driven approach to fire safety management.

4.4 Discussion on the Added Value of ST Theory and SD Modeling Approaches (Stage 5)

Figure 7 shows the interrelationship among the previously analyzed methods. This analysis explores how STS, SAs, CLD, and SD modeling are interconnected within the ST framework, progressively linking high-level system interactions to detailed, quantitative models.

At the macro level, STS defines the broader fire safety context, emphasizing the interplay between regulations, human behavior, organizational structures, and fire safety technologies. Buildings and infrastructures are not merely physical entities; they are dynamic STS where fire safety depends on the effective interaction of stakeholders, policies, and emergency response mechanisms. STS theory highlights that fire safety cannot be managed in isolation—it must be analyzed in terms of its dependencies on regulatory processes, societal expectations, and technological advancements [21, 89].

Within this broader STS framework, SAs help identify recurring patterns of system behavior that influence fire safety decision-making. Recognizing these archetypal behaviors enables fire safety engineers and policymakers to anticipate unintended consequences and adopt more resilient, long-term solutions. To translate these system patterns into a structured visual format, CLDs provide a graphical representation of the cause-and-effect relationships in fire safety systems. By mapping these relationships, CLDs help identify leverage points where interventions can have the most significant impact on improving fire safety strategies.

Finally, to move from qualitative system mapping to quantitative decision-making, SD modeling builds on CLDs by simulating the real-time behavior of fire safety systems. For example, an SD model can evaluate the long-term effects of increasing fire safety budgets on incident reduction and regulatory compliance. By integrating SD modeling, fire safety professionals can test different policy scenarios, optimize resource allocation, and enhance emergency preparedness strategies.

The ST perspective can also extend beyond the immediate scope of fire safety. When viewed from a systems perspective, fire safety is inherently interconnected with other disci-

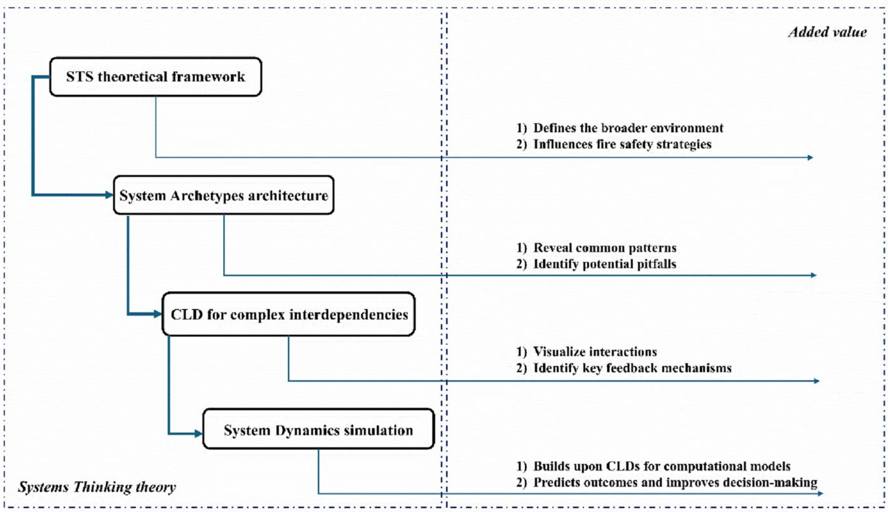


Fig. 7 Added value for FSE for each analyzed method within the systems thinking theory

plines. For example, structural design choices—such as using cross-laminated timber (CLT) instead of reinforced concrete—not only influence fire performance but also affect acoustic performance, environmental impact, and structural behavior under load. Such interactions can present synergies—such as aligning fire safety improvements with sustainability goals—but can also create conflicts that require trade-off analysis. Adopting a Systems Thinking approach at the earliest design stages enables stakeholders to evaluate these interdependencies holistically and integrate fire safety into broader performance objectives.

In conclusion, STS provides the overarching framework, SAs reveal systemic weaknesses and opportunities, CLDs visualize the interactions within the system, and SD enables simulation-based decision-making. By combining these methodologies, fire safety strategies can transition from static, rule-based approaches to adaptive, data-driven solutions that evolve with changing risks and technological advancements.

5 Future Research Directions: Challenges and Limitations (Stage 6)

This section outlines the future research lines identified from this literature review by proposing how ST tools can be applied to FSE. Considering the seven clustered research categories adopted in Sect. 4, the research needs for FSE specified by the SFPE [65], and the discussion on the current state of the art in the sections above, possible ST applications are shown in Table 10.

An ST approach can connect the different areas of a comprehensive fire safety strategy, emphasizing the interplay of materials, fire dynamics, structures, and human behavior in fire safety. By adopting SAs, CLDs, and SD modeling, such an integrated framework can enable fire safety engineers to predict, analyze, and mitigate fire risks holistically. An integrated and holistic approach could address some of the research needs identified by the SFPE, especially in the topics of decision-making, resilience, sustainability, and human behavior. Embracing emerging technologies, utilizing real-time data, establishing standardized validation procedures, exploring cross-disciplinary approaches, and focusing on policy and implementation studies will be crucial for advancing the field and addressing current gaps.

A key area for future research involves critically examining how regulatory systems interact with socio-technical systems (STS) perspectives. As highlighted in Sect. 2.2, STS frameworks allow for a richer representation of fire safety dynamics by accounting for social behaviors, informal interactions (e.g., neighbor support), and institutional actions (e.g., fire service response). However, current regulatory models often enforce simplified assumptions—such as complete occupant self-evacuation or disregarding active intervention by others. Bridging this gap requires careful inquiry into how regulations can evolve to taking into account STS-based insights, and how STS can be adopted within existing regulatory frameworks.

Finally, another promising research direction lies in applying ST to integrate fire safety with other disciplines during early-stage design and planning. Many decisions in areas such as structural design, façade system selection, and urban or spatial planning inherently influence both fire safety performance and other performance objectives such as sustainability, occupant comfort, or accessibility. Systems-based approaches can be used to model these interdependencies, identify potential synergies, and anticipate conflicts before design commitments are made. Future work should focus on developing multi-domain frameworks and

Table 10 Potential ST applications to the FSE field

Research topic	Potential application	Hypotheses for ST developments		
		SAs	CLD	SD
Fluid mechanics and fire dynamics	Fire plumes, compartment fires, tunnel fires, facades. Designing ventilation systems to control smoke spread	"Limits to Growth"—Suppression slows fire spread within certain boundaries	Map feedback effects between airflow, fire growth, and suppression effectiveness	Simulation of airflow and its effects on fire plume behavior. Test interventions (e.g., ventilation systems) for varied fire scenarios
Fire modeling and heat transfer	Developing compartment fire models for scenario evaluations. Simulate fire spread in large enclosures	"Escalation"—How uncontrolled heat transfer accelerates fire spread	Interaction between heat transfer, material ignition, and smoke production	Multi-variable simulations to test fire suppression strategies
Fire detection and suppression systems	Designing and optimizing automatic sprinklers, water mist systems, and gas extinguishers	"Shifting the Burden"—Overreliance on one suppression method reducing overall system redundancy	Relationships between system activation, water usage, and fire containment	Optimizing suppression systems' response times and efficiency
Human behavior and egress design	Planning evacuation strategies based on human behavior in fire emergencies. Designing egress strategies with consideration for visibility and movement efficiency	"Success to the Successful"—Prioritizing resources toward paths with high importance for successful evacuation	Interaction between visibility, smoke, and occupant movement	Simulate evacuation scenarios to test and improve egress designs
Risk Analysis and decision-making	Conducting quantitative fire risk assessments for buildings and products. Implementing decision analysis tools for fire safety strategies	"Growth and Underinvestment"—Rapid technology adoption increases risks without adequate safeguards	Connect innovation, safety investments, and environmental outcomes	Evaluate long-term risks and mitigation strategies for sustainable fire safety
STS-level integration	Modeling entire socio-technical systems (STS) that integrate regulatory oversight, organizational practices, occupant behavior, emergency response, and physical fire phenomena	"Eroding Goals" or "Tragedy of the Commons" may emerge when standards are relaxed or shared resources overstressed	Map feedback loops across technical, social, and institutional dimensions	Extend SD beyond fire phenomena to simulate large STSs; assess systemic interactions, resilience, and policy impacts

simulation models capable of quantifying trade-offs, such as between energy efficiency and façade fire performance, or between compact urban layouts and evacuation capacity.

6 Conclusions

The application of Systems Thinking (ST) tools and System Dynamics (SD) to the Fire Safety Engineering (FSE) field has so far been limited. Only 35 studies were found which include a direct application of an ST method to FSE, even when selected applications in nearby fields such as construction and design were included. However, multiple potential applications of SD to the FSE field were identified by considering research categorization clustering, architecture of ST tools (such as System Archetypes and Causal Loop Diagrams), and relevant previously developed models available in the literature.

A very relevant framework relies on seeing buildings and infrastructures as STS. This offers a powerful framework for addressing fire safety challenges. Another significant approach is related to the combination of SD modeling and Bayesian Networks, as has been applied for assessing the reliability of high-rise residential buildings. More generally, by analyzing factors such as fire growth rate, accident probability, and dynamic losses and benefits, SD models can provide valuable insights for developing more effective fire safety strategies and safety investment plans. Similarly, in construction and urban environments, SD has been instrumental in simulating evacuation processes, assessing the impact of safety culture, and promoting the adoption of sustainable building materials.

Considering the above, the application of ST tools in FSE is found to be a powerful method for understanding and managing the complex dynamics of fire safety in buildings and infrastructure. At the same time, SD models offer a quantitative framework for modeling such dynamics. The literature review highlights the potential versatility of SD models in addressing a wide range of fire safety challenges, such as nonlinearity, complexity, time dependence, and human behavior, across a range of industries and contexts. Despite these advancements, many challenges remain. While many studies have demonstrated the potential of SD in FSE, more case studies and practical applications are needed to validate these models and refine their accuracy and effectiveness.

The findings of this review can be structured within a three-level hierarchy of ST applications: (1) *philosophical level*—ST as a worldview that emphasizes interconnections, feedback, emergence, and holistic problem framing; *(2) methodological level*—the set of analytical approaches consistent with ST principles, including SD, qualitative system mapping, and hybrid socio-technical modeling frameworks; and, (3) *tool level*—specific techniques, such as CLDs, SAs, and simulation models, which operationalize ST methodologies. Tools and techniques from outside the traditional ST domain—such as probabilistic risk analysis—can be integrated if applied consistently with ST principles. This may require adaptations, such as embedding feedback mechanisms in risk models.

Future research could apply ST tools such as CLDs to analyze major fire events, for example the Grenfell Tower Fire. Such analyses could reveal the interplay of STS interactions and recurring SAs, such as the Tragedy of the Commons and Eroding Goals. These applications would illustrate the value of ST for understanding systemic failures and guiding improvements in fire safety governance and practice.

Additionally, future research should focus on improving the accessibility and usability of SD models for practitioners in the FSE field. Developing user-friendly tools and interfaces that allow engineers, architects, and safety managers to easily create, modify, and run SD simulations will be crucial for the widespread adoption of this methodology in practice. Collaborations between researchers, industry professionals, and software developers can facilitate the creation of more intuitive and versatile SD platforms tailored to the specific needs of fire safety stakeholders.

While this review has primarily focused on applications of ST, SD, and STS at the level of specific fire safety problems, future research could expand SD modeling to represent entire STSs. Such models would integrate technical, social, organizational, and regulatory factors in a unified framework, offering powerful insights into the systemic nature of fire safety challenges.

In conclusion, SD represents a valuable and versatile tool for advancing the field of FSE. As researchers and practitioners work to refine and expand SD methodologies, this approach can play an important role in safeguarding buildings and infrastructures from fire hazards, ultimately contributing to a safer and more resilient built environment.

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Data Availability No new data were created or analyzed in this study; therefore, data sharing is not applicable.

Declarations

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

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