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A Systems Thinking approach to balancing fire safety and sustainability in building design

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Abstract. This paper uses a Systems Thinking approach to analyse the competing objectives of fire safety and sustainability in building design. Through the explicit identification and classification of reinforcing and balancing feedback loops, the study constructs an integrated Causal Loop Diagram (CLD) that captures dynamic interactions among key variables such as material selection, building height, façade combustibility, ventilation systems, automatic extinguishing, and advanced detection systems. The analysis highlights a critical reinforcing loop that can lead to potential instabilities if left unmanaged, alongside balancing loops that naturally stabilize system behaviours. Strategic intervention points, particularly regarding innovative material development and fire protection technologies, are identified to enhance the simultaneous achievement of fire safety and sustainability objectives. The insights gained provide a clear foundation for informed decision-making, policy formulation, and resilient building practices.

1. Introduction

Fire safety and sustainability represent two critical and often competing objectives in contemporary building design and engineering. While sustainability advocates promote using eco-friendly and renewable materials, these materials—such as wood-based products—can significantly increase a building's vulnerability to fire. Conversely, materials and systems that can enhance fire resilience, like concrete and advanced fire suppression systems, frequently have higher environmental footprints due to greater resource consumption and production emissions [1]. This intrinsic tension demands a comprehensive approach to analyse and address the trade-offs effectively.

Systems Thinking, particularly the System Dynamics (SD) methodology, offers an insightful way to holistically analyse and visualize these complex interactions by explicitly identifying stocks, flows, feedback loops, and delays [2]. SD modelling, through the construction of detailed causal loop diagrams (CLDs), facilitates explicit exploration of intricate cause-effect relationships, thus allowing stakeholders to better anticipate system behaviour and proactively manage conflicting objectives [3]. In this context, discussion in previous research suggests several interlinked feedback loops relevant to fire safety and sustainability decisions in buildings. For instance, decisions regarding building height and material selection explicitly interact with sustainability and fire risk, creating reinforcing dynamics where tall buildings require substantial materials and also elevate fire risk, negatively impacting sustainability and fire safety, and thus eventually limiting feasible height [4,5]. By explicitly adopting a Systems Thinking approach (developing a Causal Loop Diagram) this paper aims to provide a clear understanding of how interventions, technological innovations, and policies can be strategically leveraged to balance and reconcile competing goals. The insights derived offer explicit guidance toward optimizing sustainable building practices without compromising fire safety and vice versa.

2. Methodology

This study demonstrates how Systems Thinking can be used to analyse and understand the complex interactions between fire safety and sustainability in building design by proposing a new conceptual model (CLD). This demonstration is done by a case study whereby a selected work of literature ([1]) is analysbweed in depth. The methodology is systematically structured in three stages:

(1) identification of causal relationships: using a scientific study [1], causal relationships between relevant variables are established;
(2) feedback loop development and classification: each loop is classified as either reinforcing or balancing based on the number of negative causal relationships;
(3) integrated Causal Loop Diagram (CLD): all validated feedback loops are integrated into a unified CLD. This CLD provides a clear, visual representation of the interactions between fire safety and sustainability, highlighting explicitly the interdependencies and the resulting system behaviour.

For developing the integrated Causal Loop Diagram and visualizing feedback structures, Vensim software is utilized considering its ease for creating clear, communicative CLD diagrams.

3. Results and discussion

By investigating [1], 18 feedback loops have been identified linked with the critical variables of fire safety and sustainability, such as building height, surface material, façade combustibility, attic design, insulation type, window area, ventilation system, local energy system, cooking systems (stoves), inspection and maintenance routines, automatic extinguishing systems, advanced detection technologies, waste management, and building characteristics (Table 1). The analysis based on the set of 18 feedback loops reveals a complex interplay between sustainability and fire safety in building design, explicitly represented through distinct reinforcing (RL) and balancing loops (BL). Reinforcing loop RL1 (Surface material selection) underscores inherent systemic instabilities where increasing concrete usage raises the carbon footprint, lowers sustainability, increases pressure for sustainable materials (such as wood), subsequently increasing fire risk, and eventually reinforcing the use of concrete again. Such loops highlight points of potential escalation or instability requiring active management and intervention.

Table 1. Feedback loops developed in this research framework.

No.	Code	Loop	Causal sequence	Meaning
01	BL1	Building height and material selection.	Building height → (+) Material Usage → (–) Sustainability Level → (-) Pressure for Sustainable Material (wood) → (+) Fire risk → (–) Building height	Taller buildings require more materials, lowering sustainability, increasing pressure for sustainable combustible materials (e.g., wood), which increases fire risk. Increased fire risk then restricts height.
02	RL1	Surface material (concrete)	Concrete material usage → (+) Carbon foot-print → (-) Sustainability Level → (-) Pressure for Sustainable Material (wood) → (+) Fire risk → (+) Concrete material usage	Increased concrete use negatively impacts sustainability, creating pressure to reduce concrete use, indirectly increasing fire risk and eventually forcing re-adoption of concrete.
03	BL2	Façade combustibility	Combustible Façade Material (FM) → (+) Fire Risk → (+) Required Fire Protection (FPL) → (+) Material Use → (–) Sustainability Level → (–) Pressure to increase sustainability → (-) Combustible Façade Material (FM)	More combustible façade materials increase fire risks, driving stronger protective measures, which reduce sustainability and subsequently discourage further combustible façade materials, thus stabilizing façade combustibility selection.
04	BL3	Attic openness and compartments	Open Attic → (+) Fire Spread Rate → (+) Fire Risk → (+) Required Fire Protection (FPL) → (+) Material Use → (–) Sustainability Level → (+) Open Attic	Open attic increases fire risk, resulting in increased protection and material use and thus reduced sustainability, eventually balancing design choices regarding attic openness.
05	BL4	Open floor design and fire risk	Open Floor Plan → (+) Flame Spread Rate → (+) Fire Risk → (+) Need for more partitioned apartment design → (–) Open Floor Plan	Open floor plans accelerate flame spread and fire risk, eventually limiting openness, stabilizing interior layout decisions.
06	BL5	Windows and insulation material- fire risk	Window Area → (-) Energy Efficiency → (-) Need for Insulation → (+) Amount of Flammable Material → (+) Fire Risk → (–) Window Area	Large window areas decrease energy efficiency, increasing insulation needs and combustible materials, elevating fire risk and then reducing window areas, creating potential fluctuations around equilibrium.
07	BL6	Windows and insulation material – sustainability	Window Area → (-) Energy Efficiency → (-) Need for Insulation → (+) Amount of Flammable Material → (+) Material use → (–) Sustainability level → (-) Pressure to reduce window area → (–)Window Area	Window areas impact energy efficiency negatively, thus requiring more insulation materials, decreasing sustainability, and stabilizing window area size.
08	BL7	Ventilation systems trade-off	Fire Dampers with mechanical ventilation → (-) Fire Risk → (+) Material Use → (–) Sustainability level → (–) Fire Dampers with mechanical ventilation.	Mechanical ventilation dampers improve safety but use more material, negatively impacting sustainability and leading to increased pressure toward natural ventilation, stabilizing ventilation choices.
09	BL8	Local energy production and fire safety	Local Energy Production Capacity → (+) Fire Load → (+) Fire Risk → (+) Need for Fire Protection → (+) Material Use → (–) Sustainability level → (+) Local Energy Production Capacity	Increasing local energy production capacity raises fire risk, requiring more protective materials and lowering sustainability, which increases pressures for local energy production capacity

Table 1. Feedback loops developed in this research framework (cont.).

No.	**Code**	**Loop**	**Causal sequence**	**Meaning**
10	BL9	Gas stoves – fire safety	Gas stoves → (+) Ignition source → (+) Fire risk → (–) Gas stoves	Gas stoves pose higher fire risks, decreasing their attractiveness and stabilizing their usage over time.
11	BL10	Gas stoves - sustainability	Gas stoves → (+) Carbon footprint → (-) Sustainability level → (-) Pressure on using electrical/induction stoves → (–) Gas stoves	Gas stove use negatively impacts sustainability, creating pressure towards electric/induction stoves, leading to significant reduction in gas stoves use over time, possibly reinforcing the transition towards sustainable cooking technologies.
12	BL11	Inspection and maintenance quality	Inspection Quality → (+) Reliability of Protection Systems → (–) Fire Risk → (+) Perceived Need for Inspection → (+) Inspection Quality	Inspection quality increases the reliability of protection systems, decreasing the fire risk. Additionally, an increase in the fire risk level can lead to higher perceived need for inspection enhancing inspection quality.
13	BL12	Automatic extinguishing systems-sustainability	Sprinkler Coverage → (+) Material Use → (–) Sustainability level → (-) Pressure to reduce sprinkler coverage → (–) Sprinkler Coverage	Increased sprinkler coverage reduce sustainability, leading to pressures reducing coverage, then stabilizing the sprinkler coverage.
14	BL13	Automatic extinguishing systems- fire safety	Sprinkler Coverage → (-) Fire risk → (+) Perceived need for sprinkler coverage → (+) Sprinkler Coverage	Increased sprinkler coverage reduces fire risk, balancing itself around stable levels of safety investment.
15	BL14	Advanced Detection Systems-sustainability	Advanced Detection System (ADS) → (+) Material usage → (–) Sustainability level→ (-) Pressure to reduce the ADS usage → (–) ADS	Increased ADS installation negatively impacts sustainability, balancing the ADS implementation.
16	BL15	Advanced Detection Systems- fire safety	Advanced Detection System (ADS) → (-) Fire Risk → (+) Need for ADS → (+) ADS	ADS reduces fire risk, lowering its perceived necessity, balancing the ADS level naturally around equilibrium.
17	BL16	Indoor Waste Storage	Indoor Waste Storage → (+) Fire Risk → (+) Required Fire Protection (FPL) → (+) Material Use → (–) Sustainability level → (+) Preference for Indoor Storage → (+) Indoor Waste Storage.	Indoor waste storage increases fire risk, reducing sustainability and thus limiting indoor waste storage decisions.
18	BL17	Site Vegetation and Accessibility	Vegetation → (+) Sustainability level→ (+) Landscaping → (–) Firefighter Accessibility → (-) Fire Risk → (–) Vegetation	Vegetation enhances sustainability but reduces accessibility, thus increasing fire risk, leading to reduced vegetation, stabilizing green area decisions.

Balancing loops, including BL1 (Building height and material selection), emphasize natural regulatory dynamics [6]. For example, increased building heights elevate material use, negatively impacting sustainability, which increases pressure for combustible sustainable materials like wood. The resultant higher fire risk eventually limits building height, achieving a self-balancing equilibrium. Similar stabilization effects are seen in loops BL2 (Façade combustibility), BL3 (Attic openness), BL4 (Open floor design), BL5 and BL6 (Windows and insulation materials), and BL7

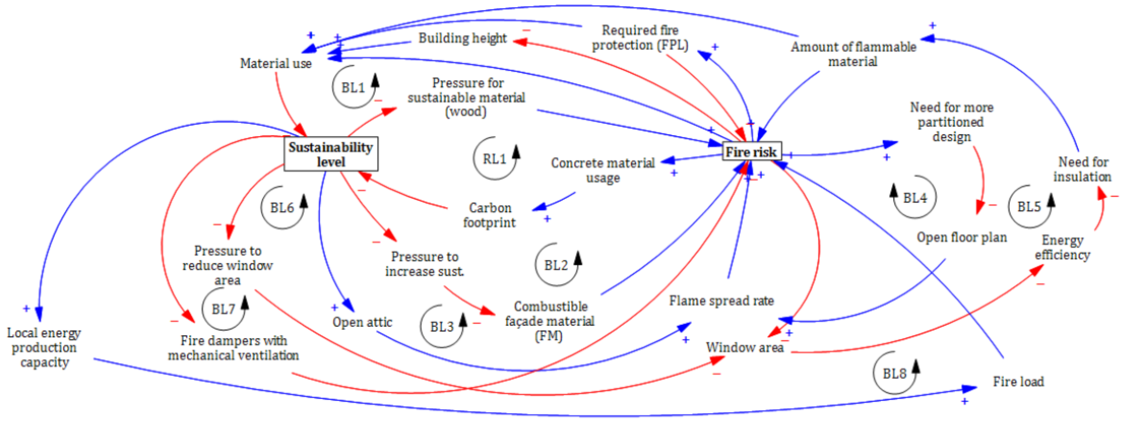

Figure 1. Causal Loop Diagram for balancing sustainability and fire safety considering the integrated feedback loops 01-09.

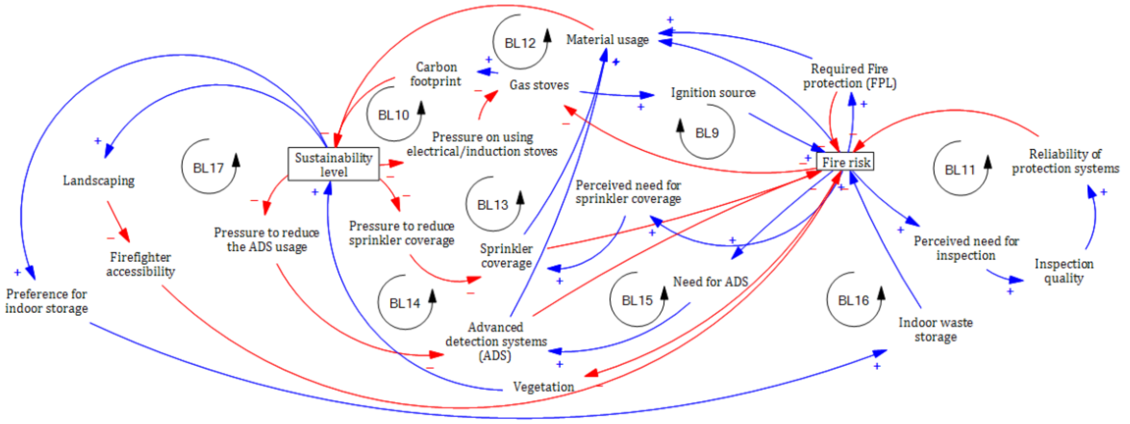

Figure 2. Causal Loop Diagram for balancing sustainability and fire safety considering the integrated feedback loops 10-18.

Note: A positive causality (blue) means that all else remaining equal, an increase in the first variable increases the second variable above what it would otherwise have been. A negative causality (red) means that all else remaining equal, an increase in the first variable decreases the second variable below what it otherwise would have been.

(Ventilation systems). The current analysis implicitly assumes insulation materials as predominantly plastic-based and thus inherently combustible.

Loops BL8 (Local energy production), BL9 and BL10 (Gas stoves regarding fire safety and sustainability, respectively), BL11 (Inspection quality), and BL12 and BL13 (Automatic extinguishing systems) collectively manage dynamic trade-offs, balancing material usage, safety, and sustainability impacts. Likewise, loops BL14 and BL15 (Advanced detection systems concerning sustainability and fire safety), BL16 (Indoor waste storage), and BL17 (Site vegetation and accessibility) explicitly illustrate the self-corrective dynamics present in the system, preventing extremes in either sustainability or fire safety measures.

The identification between balancing and reinforcing loops facilitates a deeper understanding of systemic dynamics. The integrated Causal Loop Diagram (CLD) based on these loops highlights predominant balancing feedback, demonstrating inherent robustness and equilibrium tendencies in the system. Following explicit identification and correction, an integrated CLD is developed to visualize the holistic interplay of these loops clearly (Fig. 1-2). After the integration of the 18 developed feedback loops, 111 new loops emerged starting from the variable “Fire risk”, while 109, from “Sustainability level”, indicating a highly-interconnected system. The integrated CLD, combining all loops explicitly, illustrates the dynamic interplay between fire safety and sustainability, identifying a predominant presence of balancing loops. The preponderance of balancing loops explicitly indicates a robust system that naturally regulates itself towards equilibrium states, moderating extreme behaviours. However, reinforcing loops remain critical focal points for active management to prevent unintended escalations, especially in areas related to material choices. The CLD analysis provides a refined perspective emphasizing equilibrium-maintaining mechanisms while explicitly highlighting areas of potential instability requiring strategic oversight.

4. Conclusions

The Systems Thinking approach undertaken in this study, which involved explicit identification, detailed analysis, and integration of multiple feedback loops within a structured Causal Loop Diagram (CLD), provides insights into dynamic trade-offs between fire safety and sustainability in building design. The analysis revealed a complex interplay predominantly characterized by balancing loops, signifying a natural tendency toward equilibrium. These loops ensure that building design decisions regarding sustainability and fire safety do not drift excessively toward extreme positions but stabilize around balanced equilibrium states. Specifically, balancing loops involving façade combustibility, attic openness, window areas, ventilation systems, local energy production, stove types, and inspection quality provide robust self-corrective mechanisms that counteract unintended extremes. However, the presence of reinforcing loops highlights potential systemic instabilities and areas where significant attention must be focused. The integration of these loops into a holistic CLD allowed for clear visualization of the dynamic interactions and trade-offs between fire safety and sustainability, ultimately providing guidance for strategic interventions. Future research should further quantify these relationships through System Dynamics modelling and simulations, enabling predictive analysis and scenario testing. The outcomes from such simulations would significantly enhance policymakers' and stakeholders' ability to balance fire safety and sustainability systematically and proactively, ensuring resilient, sustainable, and safe built environments.

References

1. Meacham B, Frantzich H, Mcnamee M, Kimblad E (2023) Risk and performance assessment framework for a sustainable and fire resilient building environment (SAFR-BE) Society of Fire Protection engineers Foundation. https://doi.org/10.13140/RG.2.2.16797.90089
2. Sterman JD (2002) System Dynamics: Systems Thinking and Modeling for a complex world. MIT Sloan School of Management, Cambridge MA
3. Dueñas Santana JA, Di Benedetto A, González Gómez O, Salzano E (2024) Towards sustainable hydrogen production: An integrated approach for Sustainability, Complexity, and Systems Thinking in the energy sector. J Clean Prod. https://doi.org/10.1016/j.jclepro.2024.141751
4. Meacham BJ, McNamee M (2023) Sustainable and Fire Resilient Built Environment (SAFR-BE). In: Meacham BJ, McNamee M (eds) Handbook of Fire and the Environment: Impacts and Mitigation. Springer International Publishing, Cham, pp 421–45.
5. McNamee M, Meacham BJ (2023) Conceptual Basis for a Sustainable and Fire Resilient Built Environment. Fire Technol. https://doi.org/10.1007/s10694-023-01490-9
6. Dueñas Santana JA, Salzano E, Di Benedetto A (2025) Systems Thinking for Explosion Safety Management. J Loss Prev Process Ind 105621. https://doi.org/10.1016/j.jlp.2025.105621