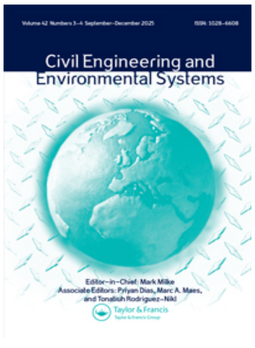

Civil Engineering and Environmental Systems

ISSN: 1028-6608 (Print) 1029-0249 (Online) Journal homepage: www.tandfonline.com/journals/gcee20

Towards a systems approach to built asset safety: challenges and an agenda

Mustafa Selçuk ÇIDIK & Mikela Chatzimichailidou

CIVIL ENGINEERING AND ENVIRONMENTAL SYSTEMS
https://doi.org/10.1080/10286608.2025.2607472

Taylor & Francis
Taylor & Francis Group

REVIEW ARTICLE

OPEN ACCESS Check for updates

Towards a systems approach to built asset safety: challenges and an agenda

Mustafa Selçuk ÇIDIK[a] and Mikela Chatzimichailidou[b]

[a]The Bartlett School of Sustainable Construction, University College London, London, UK; [b]Department of Civil, Environmental and Geomatic Engineering, University College London, London, UK

ABSTRACT
The safety of built assets is critically important, yet it is often approached in construction research and practice through a narrow lens focused on technical compliance and procedural risk mitigation. This contrasts with contemporary safety science, which frames safety as an emergent, system-level outcome shaped by complex socio-technical interactions. To address this gap, this paper introduces the Integrated Systems Approach to Lifecycle Safety as a conceptual foundation for construction professionals to rethink how safety is conceived and managed throughout the lifecycle of built assets. Drawing on literature in systems integration, the paper critiques the current delivery-oriented focus of integration practices that reinforce compartmentalisation and limit cross-system coordination. Integrated Systems Approach to Lifecycle Safety is not presented as a prescriptive framework but as a directional concept encouraging a more holistic, adaptive approach to safety. The paper identifies 23 non-exhaustive interrelated challenges across five types of integration templates – product, lifecycle, regulatory, contractual, and digital – grouped into three intersecting domains: conceptual orientation, practical orientation, and capabilities. These domains are proposed as critical areas for collective action, offering a foundation for future research, practice, and policy that reframes safety as a dynamic and continuously assured system-level concern.

ARTICLE HISTORY
Received 17 June 2025
Accepted 16 December 2025

KEYWORDS
Built asset; construction; safety; systems engineering; systems integration

1. Introduction

Understanding the lifecycle of built assets requires attention to the complex web of interactions they involve. On one hand, design, delivery, operations, maintenance, and decommissioning involve coordination among numerous social actors and technological components. On the other hand, once delivered, these assets interact with, and become part of, the built environment, which plays a major role in shaping the wider physical and social environments. Thus, the challenges associated with grasping and

CONTACT Mustafa Selçuk ÇIDIK s.cidik@ucl.ac.uk University College London, Gower Street, London WC1E 6BT, UK

managing the lifecycle of built assets, as well as their relationship with natural, social, and operational environments, have been ongoing areas of academic, policy, and practitioner interest (Bijker, Hughes, and Pinch 1987; Jasanoff 2004; Kordi, Belayutham, and Che Ibrahim 2021; Koskela 2008; Noktehdan et al. 2019).

Given this complexity and diversity, 'safety of a built asset' has multiple facets and meanings. Different research traditions emphasise different facets of safety: some focus on occupational health and safety (OHS) during construction; others examine design-stage interventions through Design for Safety (DfS) (Ibrahim et al. 2022; Samsudin et al. 2022) or Prevention through Design (PtD) (Schulte et al. 2008); while others address safety in use, including fire safety, structural robustness, or the safety implications of interactions between built assets and their wider natural and social environments. These perspectives have generated valuable insights but remain largely siloed, each addressing specific lifecycle stages, stakeholder groups, or technical components, without accounting for how different safety concerns interact or shape one another over time. This fragmentation creates conceptual and practical challenges for understanding and managing the safety of built assets in a comprehensive way. Recent tragedies such as the fire at the Grenfell Tower in the UK and the collapse of the Morandi Bridge in Italy, among others, once again demonstrated that safety of built assets needs to be understood and dynamically managed as a system feature and a fundamental framing requirement. This is needed to properly address the safety of built assets while recognising the (1) complexity and uncertainty involved in their lifecycle, and (2) their embeddedness in wider natural, social and operational environment.

An influential conceptual response to grasping and working with the lifecycle complexity of the built assets has been the application of systems engineering principles (Watson 2019). This sees construction projects as an endeavour of system delivery and argues for an understanding of the built asset as a system that interacts with and is embedded within broader environmental, social, and operational systems, forming a system-of-systems (ICE 2020; Locatelli, Mancini, and Romano 2014; Whyte 2018). A key concept that has emerged in this literature is 'systems integration', which is now considered a key part of construction project management, particularly for complex projects such as large infrastructure projects (IPA 2021; Whyte and Davies 2021; Whyte, Davies, and Sexton 2022). The concept of systems integration highlights the importance of interactions between new and pre-existing natural, built, and operational systems, and emphasises the need to design, deliver, and combine multiple individual systems to function as one all-encompassing system of systems (IPA 2021).

However, the application of the notion of systems integration has mainly remained focused on technical/technological aspects and primarily aimed at assuring the delivery of project outputs and the associated costs. In this formulation, safety is side-lined as a matter of technical compliance with fragmented regulations across the built asset lifecycle, rather than being addressed as a dynamic challenge requiring coordination across interconnected technical and organisational systems, as suggested by contemporary safety science literature (e.g. Oginni et al. 2023; Patriarca et al. 2018; Woods 2015). This narrow framing limits the ability of project professionals to recognise and act upon the lifecycle implications of their decisions for the long-term safety of built assets.

This paper introduces an Integrated Systems Approach to Lifecycle Safety (ISALS) as a conceptual foundation that adopts the perspective of construction project professionals and proposes how safety can be understood, coordinated, and assured across the full lifecycle of built assets. ISALS treats safety as a continuous concern emerging both from the interactions involved in the delivery of the built asset and from its operation within wider natural, social, and operational environments. ISALS recognises that the safety of built assets cannot be ensured through fragmented compliance or technical processes alone, and that project professionals must coordinate more effectively with the technical, organisational, and social actors involved across the lifecycle to support safer system outcomes. To enable such an approach, systems integration must evolve beyond a narrow focus on technical delivery to incorporate lifecycle continuity and the alignment of diverse responsibilities, perspectives, and interfaces that shape safety outcomes. Drawing on Whyte and Davies (2021) process perspective, which emphasises emergent complexity and uncertainty, the paper examines the conceptual and practical challenges that arise when seeking to embed this systems-oriented understanding of safety into construction practice.

While systems approaches have been applied within construction OHS research, they typically centre on the work system of those undertaking physical construction or maintenance tasks. In contrast, ISALS – and the argument presented here – focus on the safety of the built asset itself once delivered and throughout its lifecycle. This relates to its design, construction, operation, adaptation, and end-of-life phases, as well as its interactions with wider natural, built, and operational environments. The perspective adopted is that of project professionals, whose decisions play a central role in shaping asset-level safety outcomes. Although safety is ultimately co-produced by multiple actors (e.g. users, regulators, operators), the paper focuses on the levers of intervention available to project professionals within this broader context.

The aim of the paper, therefore, is to conceptualise a systems-oriented, lifecycle-focused approach to the safety of built assets grounded in the perspective of project professionals. The paper identifies the limitations of current systems integration practices in supporting such an approach and offers ISALS as a directional concept and accompanying research agenda for enabling lifecycle safety in construction. The focus is explicitly on the safety of built assets, rather than solely on occupational health and safety during construction activities.

The paper addresses the following research questions:

– What are the key considerations and challenges for construction professionals in achieving an ISALS?
– How can systems engineering principles and systems integration practices help construction professionals in achieving ISALS?
– What are the challenges of, and ways forward for, incorporating safety into the existing processes and practices of systems integration in construction to enable ISALS?

While ISALS is not presented as a fully developed framework, the paper provides a structured conceptual basis for rethinking how safety is integrated within systems engineering and systems integration practices. By critically examining existing integration templates and practices and highlighting their limitations in addressing safety as a lifecycle-wide concern embedded within broader contexts, the paper seeks to reposition safety as a dynamic and continuous objective throughout the lifecycle of built assets. In doing so, ISALS serves as a directional conceptual foundation – a starting point for future empirical, methodological, and policy work aimed at embedding lifecycle safety more effectively in the conception, delivery, and operation of built assets.

Bridging existing safety-related observations and the systems integration literature, this paper makes a threefold contribution. First, it conceptualises lifecycle safety of built assets through the ISALS perspective, framing safety as a property shaped by interactions and dependencies across the full asset lifecycle. Second, it extends current understandings of systems integration by identifying the limitations of prevailing practices for ensuring lifecycle safety and outlining how technical, organisational, and social dimensions might be more effectively aligned to co-produce safety across complex construction projects. Third, it provides guidance for project professionals and offers a directional concept and research agenda to inform future empirical, methodological, and policy work on lifecycle safety of built assets.

In the remainder of the paper, we first introduce the notions of systems engineering and systems integration with a focus on their application in the construction context. We then establish the theoretical framework of the paper and argue that systems integration could help construction professionals in achieving ISALS. The subsequent section explores the shortcomings of the existing templates of systems integration in supporting ISALS. Finally, based on these challenges, we develop an outline agenda to guide future academic, practical and policy efforts for moving towards ISALS in construction.

2. Systems engineering and systems integration in the construction context

Systems engineering emerged from the need to deliver complex projects in the USA military and aerospace industries (Johnson 1997). According to the theoretical foundation of systems engineering, the whole is more than the sum of its parts (Dekker, Cilliers, and Hofmeyr 2011). Practically, this means that attention should be given to making constituent parts of systems function cohesively (Whyte and Davies 2021), as the success of a system can only be determined in the context of the whole (Leveson 2016). The 'whole' comprises the relationships between sub-systems and components that should work together towards a common purpose. It is this need for coherence between constituent parts of a system that makes systems integration a key consideration.

The notion of systems integration arose early in the twentieth century through work on systems engineering. Following World War II, the world's first dedicated systems integrator firm, Ramo-Wooldridge Corporation in California, USA, worked across organisational boundaries on the Atlas missile defence project, coordinating contractor activities and integrating the development of sub-systems (Mahnken 2008). Since its early days, systems integration has been defined and studied in various ways. According to the SEBoK (2021), systems integration consists of taking delivery of the implemented system elements, assembling these elements together, and performing verification and validation actions during the assembly. Systems integration is part of the realisation effort and relates specifically to developmental items (SEBoK 2021). The integration process aims to synthesise system elements into a realised system (product or service) that satisfies system requirements, architecture, and design (ISO/IEC/IEEE 15288: 2015). Thus, systems integration ensures individual system elements function coherently as a whole and satisfy system design characteristics (SEBoK 2021).

The growing interest in systems integration in construction is closely tied to the increasing complexity and unpredictability of major projects (Flyvbjerg 2017; Whyte and Davies 2021). As built assets become more technologically sophisticated and socially embedded, their delivery involves a wider range of interdependent systems, stakeholders, and environments. In response, systems integration has gained prominence as a strategy for coordinating these elements to ensure that projects function coherently, not just at the point of delivery, but across their entire lifecycle. Organisations such as the UK's Institution of Civil Engineers (ICE) and the Infrastructure and Projects Authority (IPA) have promoted systems integration as essential to achieving reliable performance in infrastructure projects. It involves aligning and combining multiple subsystems into a unified whole and ensuring their incorporation into broader system-of-systems environments (SEBoK 2021; Whyte 2018). This need has been evident in projects such as Heathrow Terminal Five, Crossrail, and High Speed rail 2, where integration challenges led to serious disruptions and late-stage issue detection (Whyte, Davies, and Sexton 2022).

Crossrail, for instance, exemplifies systems integration in construction, as the project's performance and operational outcomes depended heavily on decisions made during the construction stage. Coordination of tunnelling, track installation, signalling, power supply, ventilation, fire safety, and station facilities – including their respective teams – had to ensure that these systems would function seamlessly once the line became operational. For example, the placement of mechanical and electrical systems during construction affected passenger flow, safety responses, and reliability in daily operations. The line's overall safety, efficiency, and performance emerged from the careful integration of these interconnected systems and the choices made during construction, highlighting how early decisions and understanding of the end product shape long-term operational success of the built asset.

As projects grow in scale and complexity, with increasing numbers of components, interfaces, and organisational actors (Shenhar and Dvir 2007), they also face heightened uncertainty driven by technological change, market volatility, and shifting societal expectations (Brady and Davies 2014; Lenfle and Loch 2010). Whyte and Davies (2021) argue that systems integration helps manage these dynamics through structured coordination across boundaries, using mechanisms such as interface management, defined roles, and collaborative practices.

Although applying systems integration in construction has become mainstream, the majority of literature primarily targets enhancing delivery performance, operability and profitability (e.g. Denicol, Davies, and Krystallis 2020; Whyte 2016; Whyte and Davies 2021). However, beyond these aspects, safety is a fundamental system property that also demands attention. Existing safety research in construction predominantly focuses on OHS during asset delivery, neglecting a holistic view of built asset safety across design, delivery, and operations. Ensuring the operational safety of infrastructure is vital for maintaining essential services, protecting people and environments, and supporting broader social, technological, and economic developments (Dunn and Gonzalez-Otalora 2021). Tragedies such as the Grenfell Tower fire illustrate the need to consider high-risk buildings as complex systems to understand and manage their safety appropriately during their operations (Çıdık and Phillips 2021; Hackitt 2018). Hence, systems integration, through its integrated approach to system design, delivery, and operations, offers a promising conceptual foundation for ISALS for construction professionals.

3. Reframing safety as a system-level outcome in systems integration

Despite its importance, safety has remained largely marginal in systems integration discourse within construction and project management, where emphasis often lies on technical coordination and timely project delivery. At the same time, approaches that integrate safety considerations into the design phase of construction projects, such as DfS and PtD (Ibrahim et al. 2022; Samsudin et al. 2022; Schulte et al. 2008), primarily aim to protect workers by reducing or eliminating hazards before construction begins. They emphasise early risk identification, which can also indirectly benefit public and operational safety, however, they have several limitations in the argument presented herein. They are often resource-intensive, depend on previous similar experience, and require accurate hazard identification, which can be incomplete in complex or novel projects. Their primary focus on occupational safety can overlook broader systemic, societal, or environmental risks, and they tend to adopt a linear (i.e. cause–effect), project-centric perspective that may fail to account for interactions across processes, supply chains, and organisational systems. Moreover, novel construction methods, materials, and digital technologies can introduce unforeseen hazards and emergent risks that cannot be fully anticipated, limiting the effectiveness of DfS and PtD in addressing uncertainties inherent in complex and innovative construction projects. For instance, from a DfS perspective, the Grenfell Tower fire in the UK highlights the limits of focusing solely on safety during the design phase. While DfS seeks to minimise hazards through planning and specifications, the disaster emerged from a complex interplay of factors beyond design alone, including construction practices, later material choices, regulatory failures, supply chain omissions, and organisational decision-making. This demonstrates that ensuring safety requires a holistic, whole lifecycle approach rather than relying on design interventions in isolation.

Hence, safety is not an isolated attribute or outcome that can be engineered independently; it is an emergent property of socio-technical systems. It arises from the dynamic and interdependent interactions between technical components and organisational actors, rather than being confined to individual parts (Oginni et al. 2023; Patriarca et al. 2018; Woods 2015). The safety of built assets, in particular, as an emergent property, arises from the combined interactions among design, technology, operations, and human behaviour, rather than from any single component or system. This understanding aligns with the concept of 'emergent complexity', as developed by Whyte and Davies (2021), which describes how construction projects exhibit non-linear, path-dependent behaviours that evolve unpredictably over time. For example, a non-linear behaviour could manifest when a minor delay in material delivery cascades into replacement of that material without enough due diligence due to already happened scheduling problems, thus creating safety risks. Path-dependent behaviour, on the other hand, may result from early design choices or construction methods that establish constraints, thereby limiting flexibility of design or occupational choices in later stages of the built asset lifecycle. Fragmented and interdependent project phases – design, manufacture, installation, operation – introduce significant technical complexity, while diverse and distributed actors create organisational complexity. When these dimensions intersect, the safety performance of a built asset becomes non-deterministic, shaped by interactions across system boundaries (Allocco 2010; Perrow 1984; Reason 1997). Safety science, particularly systems-oriented traditions (Leveson 2016; Rasmussen 1997), highlights the need to address this complexity by embedding safety into both technical and organisational coordination from the outset and across the lifecycle.

In this context, emergent uncertainty refers to the extended, dynamic, and unfolding nature of both project delivery and the operational lifespan of built assets. The challenge of anticipating short-term outcomes in construction projects – and long-term consequences in asset operation – stems from these layers of technical and organisational uncertainty. The near-term uncertainties around project delivery are well documented in construction research, encapsulated in the idea that 'project information is never complete until the project is completed' (Winch 2006). Yet, beyond the delivery horizon lies a second, longer-term uncertainty that surrounds the asset's operational future. Societal shifts, environmental change, market volatility, and technological advancements contribute to this longer-term emergent uncertainty (Whyte and Davies 2021), compounding the complexity of making robust, forward-looking safety decisions. These dynamics directly influence the ability of a project to stay aligned with its intended goals, particularly long-term safety performance. Addressing both types of uncertainty together is essential to ensure safe operation across the evolving configuration of built assets and the systems they interact with.

Nevertheless, the ongoing nature of technological and organisational uncertainty presents a profound challenge to ensuring safety across the lifecycle of built assets. A recurring theme in safety science is that safety depends on continuous learning. Diverse strands of safety research, ranging from standardisation and benchmarking to accident investigation and near-miss analysis, emphasise the importance of learning from the past to manage future risks. However, in contexts marked by emergent uncertainty in both project delivery and asset operation, the capacity to extrapolate from past events becomes inherently limited. This presents a major barrier to maintaining safety over time. Empirical research in occupational safety in construction reinforces this issue, with numerous studies highlighting how rapidly changing physical and organisational conditions on construction sites hinder efforts to maintain safe practices (Sherratt and Ivory 2019). Although some researchers have conceptualised safety as a dynamic and adaptive phenomenon, they have not yet addressed the specific implications of emergent uncertainty as it manifests in construction systems over time.

While emergent complexity and uncertainty are analytically distinct, they are deeply interconnected. Complex interactions can result in delayed or unanticipated effects, increasing uncertainty, while uncertain conditions often drive the need for flexible system configurations, adding further complexity. Systems engineers, in responding to future unpredictability, often introduce such configurations, inadvertently amplifying system complexity. Understanding the interplay between these forces is essential for rethinking systems integration as a tool for safety. In this context, ISALS becomes vital; one that explicitly integrates complexity and uncertainty into how safety is conceived, planned, and managed throughout the built asset lifecycle.

4. Challenges of considering safety in systems integration

As outlined in the previous section, current approaches to systems integration address emergent complexity and uncertainty primarily through structural coordination mechanisms. However, these efforts have not meaningfully incorporated safety as a system-level concern. In this section, we argue that existing templates and practices of systems integration – developed to address emergent complexity and uncertainty in construction projects – have been predominantly shaped by goals related to delivery performance, operability, and profitability. As a result, safety has not been a central concern in systems integration practices within construction; the gap that we are prioritising and aim to address in this work. Following a brief clarification of our use of the notions of 'templates' and 'practices' in this context, we discuss their inadequacy in enabling an ISALS. This sets the foundation for theoretical and practical improvements, which we further explore in the discussion section.

4.1. Templates and practices in systems integration

Appropriate simplification rules and structures are essential to systems integration. These enable organisations to manage emergent complexity and uncertainty (Whyte and Davies 2021; Sull and Eisenhardt 2015). Such rules are embedded in engineering and project management, where technical and organisational complexities intersect. For example, construction projects make extensive use of breakdown structures – work breakdown structures, cost breakdown structures, and organisation breakdown structures – that offer simplified and decomposed views of construction activities, financial flows, and roles and responsibilities. While these templates do not resolve emergent uncertainty on their own, they provide a baseline for understanding and navigating complexity (Whyte and Davies 2021). In this paper, we define 'templates of systems integration' as simplifying structures and rules that support technical and organisational coordination across construction projects.

However, the application of these templates is rarely straightforward. Engineering and project management studies have shown that practitioners often adapt and evolve templates in practice to respond to unfolding complexity (e.g. Brusoni and Prencipe 2001; Henderson and Clark 1990). For example, knowledge structures are rarely linear and evolve through a dynamic entanglement of product and organisational elements (Frigant and Talbot 2005). Similarly, shared temporal templates, though used to structure integration activities (Whyte and Davies 2021; Orlikowski and Yates 2002), are often contested and reshaped by different actors (McGivern et al. 2018). Therefore, in what follows, we examine how product, organisational, temporal, regulatory, contractual, and digital templates and their associated practices pose challenges for incorporating safety into systems integration. We argue that current templates and practices of systems integration are not fit for enabling ISALS, and thus integrating safety as a system-level outcome requires rethinking these structures and their use in practice.

4.2. System modelling templates and coordination practices

4.2.1. Breakdown structures and task coordination

Breakdown structures are commonly used in the design and delivery of construction projects to decompose both the technical product and the organisational arrangements. Technological systems, as well as how they can be delivered and operated, are typically conceptualised through such structures. However, within current practices, it remains unclear and unstandardised which breakdown structures (e.g. work, function, contract) are used by safety professionals to ensure the safety of the built assets being designed and delivered. While prior literature on systems integration has explored how breakdown structures coordinate design, delivery and operational tasks (Whyte and Davies 2021; Whyte, Davies, and Sexton 2022), to the authors' knowledge, these structures have not been evaluated in terms of how they support coordination of safety across the technical, organisational, knowledge, or lifecycle boundaries in construction projects.

Existing breakdown structures emphasise compartmentalisation, underpin risk identification (as opposed to risk assessment), and tend to reinforce a blame culture. In essence, compartmentalisation shifts attention away from the whole and toward the parts, limiting the identification of causal scenarios that emerge across system interactions. This obstructs early elimination and control of potential loss events. These structures are rooted in reductionism, which contradicts the systems-based view of safety as a system-level outcome; one that cannot be assessed through isolated analysis of components or reassembled from part-level evaluations (Leveson 2016). This component-based thinking reinforces narrow, outdated assumptions about causality, such as linear cause–effect chains or single points of failure, thereby promoting a culture of blame rather than one of systemic learning. Although breakdown structures help identify and assign risk ownership, they do so in a fragmented manner and do not inherently prioritise mitigation. Moreover, they are poorly suited to capturing the non-linear and interface-driven nature of risks in complex socio-technical systems. Existing risk quantification methods, which rely on isolated component probabilities and assumptions of independence, fail to account for software issues, interaction effects, and the cognitive and organisational factors that contribute to accidents (Leveson 2016). Thus, current systems integration practices do not adequately reflect the complexity of safety of built assets as a system-level outcome.

One of the key challenges of systems integration in construction is managing the use of fixed breakdown structures while the project definition and scope are still evolving. It is particularly difficult to understand and manage how design decisions and changes will impact the performance of the project as a whole, especially in complex projects (Whyte, Stasis, and Lindkvist 2016). This complexity is compounded by the involvement of numerous specialists, who are responsible for different parts of the design and often operate under different organisational umbrellas with differing perspectives and priorities. It is only through continuous coordination and collaboration that these specialists can ensure the evolving design meets project requirements (Whyte and Davies 2021). However, safety remains a distinct and under-addressed concern within design development and change management processes. In most cases, safety is not expressed as a primary design goal or requirement. It is typically treated as a matter of regulatory compliance, with a focus either on component-level safety (e.g. ensuring the safe operation of a power generator) or sub-system safety (e.g. a heating system), depending respectively on manufacturer specifications and building codes (Çıdık and Phillips 2021). As a result, ongoing collaboration and coordination around design development rarely centre on optimising safety as a system-level outcome, and safety requirements are usually treated as secondary concerns to be addressed after operational key performance targets have been defined. In addition to these challenges, safety integration is also constrained by how lifecycle phases are structured and coordinated across time which we discuss in the next section.

4.2.2. Lifecycle templates and lifecycle coordination practices

Integration across different lifecycle phases remains a well-recognised challenge in construction. The most extensively studied disconnect is between the design and construction phases, where divergent priorities and fragmented responsibilities undermine performance and coordination. Collaborative approaches such as relational contracting (Chan, Chan, and Yeung 2009) and early contractor involvement (Mosey 2009) have emerged to address these issues. More recently, lifecycle-focused initiatives such as 'soft landings' (BSRIA 2018) and the 'golden thread of digital information' (Chatzimichailidou and Ma 2022; Mêda, Sousa, and Hjelseth 2020) have aimed to strengthen continuity between delivery and operational phases. The Grenfell Tower tragedy starkly demonstrated the dangers of failing to integrate safety meaningfully across the lifecycle, particularly at the interface between delivery and operations (Hackitt 2018). However, even these efforts tend to prioritise delivery performance and benefits realisation, while treating safety in linear and procedural terms, often focused on record-keeping rather than systemic risk management (Çıdık and Phillips 2021). Although there has been some interest in integrating OHS at early design stages (e.g. Ibrahim et al. 2022), this typically pertains to the safety of construction work environments rather than to the long-term safety of the built asset itself. As a result, there remains no sustained line of sight for safety across the full lifecycle of the asset, from design and construction through to operation and eventual decommissioning.

Therefore, one of the core issues in current systems integration practices is the limited and delayed consideration of safety within lifecycle planning templates, as well as the misalignment between system delivery and operations, where safety is often interpreted inconsistently. Construction projects typically use lifecycle templates that segment the project into discrete stages, but these templates rarely treat safety as a primary concern at the outset. It remains common for safety analysis to be introduced late, for example, through a hazard list requested by the client after design options have already been selected. This reflects a broader tendency to treat safety as a compliance item, rather than as a design and integration priority. When safety is eventually considered later in the project lifecycle, it is often based on templates and tools that are misaligned with those used in system delivery and integration (Oginni et al. 2023). This introduces inconsistencies in how hazards are identified, how safety requirements are generated, and how these are managed across technical and organisational interfaces.

Meanwhile, systems integration in construction increasingly involves connecting individual projects with broader systems of systems. Built assets, such as railway lines, data centres, or housing developments, must function not only as standalone systems, but also as components within wider infrastructure, mobility, social, and ecological systems. Yet current systems integration practices do not frame safety as an emergent and evolving concern across these broader configurations. Instead, safety is often reduced to a matter of regulatory compliance at a small number of operational touchpoints. This static view limits the ability to anticipate and manage the dynamic risks associated with long-lived and interconnected systems. This is particularly problematic given the inherent uncertainty in how systems of systems will evolve. Built assets are shaped by – and shape – broader environments whose requirements and risks shift over time due to technological, social, regulatory, and environmental change. What is considered safe today may not be sufficient tomorrow. Ensuring long-term safety thus requires a more adaptive and future-facing approach to integration, one that can account for changing expectations, emerging hazards, and evolving interdependencies.

However, the safety implications of these evolving systems are often poorly understood. In many cases, they are only discovered after incidents occur. A central barrier to addressing this proactively is the limited availability of capabilities, knowledge, and tools needed to anticipate future safety needs. Because safety is often learned through past experience, the uncertainty of future systems contexts makes it difficult to define safety requirements in advance. Recognising this challenge is essential for enabling an ISALS. It highlights the need for continuous development of safety-related competencies and knowledge practices that can evolve alongside system conditions and societal expectations. Finally, given the likelihood of abrupt and non-linear changes to the operating context of built assets, driven by climate change, political disruptions, or economic crises, it is essential that built assets are designed and integrated to remain safe under new and unforeseen conditions. This aligns with the notion of resilience but shifts the emphasis from post-disaster operational recovery to the ongoing preservation and adaptation of safety across complex and uncertain system lifecycles (Bosher 2008; Murtagh, Scott, and Fan 2020).

4.3. Regulatory templates and practices

The current regulatory system in construction is highly complex, involving multiple oversight bodies, routes to compliance, duty holders, and overlapping legislative frameworks. In practice, this system often reinforces a fragmented approach to safety, aligning regulations with specific trades, disciplines, or asset components. This siloed structure makes it difficult to understand or manage the systemic consequences of design or operational decisions, an issue starkly illustrated by the Grenfell Tower fire (Hackitt 2018). The tragedy underscored the need for a regulatory approach that treats the built asset as a complex system, not just a collection of isolated parts. To address these challenges, a shift toward a performance-based regulatory regime has been proposed. Such an approach moves beyond prescriptive, component-level rules and aims to support more integrated, outcome-focused safety practices (Barua, Gao, and Mannan 2016). This would also allow for greater responsiveness to innovation and changing technologies. However, current efforts in this direction are constrained by a widespread lack of system safety competence among construction professionals (Spinardi and Law 2019). Bridging this gap would require not only regulatory reform but also substantial investment in developing professional capacity and systems thinking across the sector.

A further limitation of existing regulation is its stage-specific orientation. Most frameworks focus on individual lifecycle phases, such as design, construction, or occupancy, without providing a structure for managing safety across the full lifecycle of a built asset. An important exception is the work by Meacham and van Straalen (2018), who examine the building regulatory regime as a socio-technical system and identify the broad institutional, cultural, and professional shifts required to support more integrated approaches to safety. Their work offers a foundation for imagining how a lifecycle-oriented, systems-based regulatory model could function in practice. Another major concern is the lack of attention to equitable safety outcomes. High-profile events such as the Grenfell fire have revealed how residents from less privileged backgrounds, particularly those in social housing, are disproportionately affected by systemic safety failures (Hernández, Moghadam, and Lombardi 2024). These disparities also extend to operational and maintenance staff, whose working conditions are often overlooked during the design process, leading to avoidable safety hazards once the asset is in use (Samsudin et al. 2022). These examples underscore a broader concern: current regulatory frameworks do not adequately address the unequal ways in which different user groups interact with and are affected by built assets over time.

A systems integration perspective that places safety at the centre of regulatory templates and practices would therefore require a fundamental shift. Rather than regulating for an 'average' user or fixed scenarios, such a perspective would involve identifying and addressing user needs, system interactions, and emergent risks across the asset lifecycle holistically. This implies a more inclusive, adaptive, and forward-looking approach to regulation, one that is capable of supporting safety as a system-level outcome.

4.4. Contractual templates and practices

Contractual templates in construction projects are closely aligned with existing breakdown structures and regulatory frameworks. Typically, contracts reflect the decomposition of work into packages and mirror regulatory roles and responsibilities, such as those defined under the UK Construction (Design and Management) Regulations 2015 (Health and Safety Executive 2015). While this approach brings clarity to deliverables and legal accountability, it also reinforces the fragmented logic of project delivery, treating the built asset as a set of isolated outputs rather than an integrated system nested within system-of-systems. A key limitation of this model is that, while safety is typically addressed in contracts through compliance-based obligations – particularly in relation to OHS – it is rarely framed as a systemic performance objective or as an integrated design requirement for the built asset itself. Contracts generally focus on what is to be built, not how emergent system properties, such as safety, are to be achieved and assured across the lifecycle. As a result, holistic safety considerations often fall outside the defined scope of work packages and are not embedded in contractual expectations or project-wide performance criteria. This limited framing allows important system safety aspects to be marginalised or deferred. When safety concerns do arise, they frequently lead to contractual tension, requiring changes that introduce delay, cost, or conflict. The result is a project structure that prioritises the so-called 'iron triangle' of time, cost, and specification compliance, often at the expense of broader goals such as operational resilience, learning, or the safe functioning of the asset over time.

The distinction between OHS and built asset safety is important here. While OHS is typically well-accounted for in contracts through clear, role-based accountability structures, system-level asset safety is not. Unless explicitly required by the client, roles responsible for asset-level safety tend to emerge informally and late in the process, often after technical disciplines determine that safety must now be addressed. These roles are typically temporary, interpreted differently across projects, and shaped by the internal norms of each contractor, rather than formalised through standardised contracts. This lack of contractual clarity is also reflected in how safety is analysed and assured. In most cases, the methods for conducting safety analysis are not defined in contractual terms. Instead, subject matter experts rely on generalised hazard lists and past experience to guide their assessments. For example, generic hazard lists such as those provided by the UK Rail Safety and Standards Board (RSSB 2023) offer a starting point but focus primarily on known, isolated hazards. They are less effective at identifying risks that arise from system interactions or from the integration of human, organisational, and technical elements. Safety analysis outputs are typically captured in spreadsheets and reports and returned to clients as standalone documentation, such as hazard logs or safety requirement lists. This manual, siloed process makes integration, traceability, and assurance difficult and resource-intensive (Oginni et al. 2023).

From a systems integration perspective, these limitations are significant. Contracts shape how responsibilities are distributed, how design and delivery are coordinated, and how success is measured. When holistic safety is not embedded in the contractual logic of the project, it remains peripheral, often reliant on individual expertise, informal coordination, or late-stage documentation. This highlights a broader challenge: contractual obligations tend to focus on regulatory compliance rather than on the integration of safety as a system-level outcome that needs to be approached from a lifecycle perspective and designed, coordinated, and assured across organisational boundaries and lifecycle stages.

4.5. Digital templates and practices

The digitalisation of construction has been widely promoted as a way to improve coordination, decision-making, and lifecycle integration, particularly during the design and delivery phases, through enhanced information management (Chatzimichailidou, Whitcher, and Suzic 2024; Çıdık and Boyd 2022). Central to this effort are ideas such as the ‘single digital source of truth’, which aim to ensure consistency and traceability across fragmented teams and systems. These concepts are often associated with better delivery and operational outcomes, and increasingly, with improved safety, particularly through real-time monitoring, simulation, and compliance tracking. However, the primary focus of digital safety tools to date has been on OHS. While these applications offer valuable functionality, such as hazard detection and behavioural tracking, they remain narrowly focused and reinforce a fragmented, task-specific view of safety. As such, they do little to support safety as a system-level outcome that emerges over time from the complex interactions of technical, organisational, and human systems.

One of the few digital initiatives aimed explicitly at lifecycle safety – the ‘golden thread of digital information’ – gained visibility in the aftermath of the Grenfell Tower fire, where breakdowns in safety accountability and information continuity were central concerns (Hackitt 2018). The golden thread aspires to provide a continuously updated digital record of safety-related decisions, design rationales, and risk assessments across the asset lifecycle. While this ambition is promising, its implementation remains limited and inconsistent. More fundamentally, it faces a persistent challenge: the gap between information availability and meaningful communication. As Çıdık and Phillips (2021) argue, the presence of a digital record does not guarantee that information will be interpreted, acted upon, or shared effectively, especially in fragmented or adversarial project environments. This issue is amplified when complex, context-specific knowledge is reduced to structured data formats. Codification can strip away the nuance needed for interpretation, particularly across disciplines or at human – machine interfaces (Çıdık, Boyd, and Thurairajah 2017). Although structured digital environments offer traceability, they often lack the flexibility to support the situated, interpretive practices necessary for systemic safety coordination.

From the perspective of an ISALS, this points to a critical limitation in current digital integration efforts. Safety is not only about what information is captured, but how it is interpreted, shared, and acted upon across organisational and temporal boundaries. While digitalisation holds clear potential, its value for ISALS ultimately depends on how well it is embedded within collaborative, adaptive, and meaning-making project and operational practices, not just its technical capacity for data storage or traceability.

4.6. Consequences of template limitations

The limitations of current systems integration templates are not merely theoretical concerns; they have real-world consequences. When these templates fail to support safety as a system-level, lifecycle-spanning concern, they can contribute to the emergence of serious risks that remain undetected or unmanaged until it is too late. The following examples of the Grenfell Tower fire and the Morandi Bridge collapse illustrate how the combined shortcomings of these templates can lead to systemic safety failures. These cases demonstrate the urgent need to reconceptualise safety not as a fragmented compliance task, but as a dynamic and continuously assured outcome embedded across the entire lifecycle of built assets.

The Grenfell Tower fire tragically illustrates how the interplay of multiple flawed systems integration templates can result in catastrophic safety failures. Lifecycle templates failed to ensure continuity of safety considerations from design through to operation. Safety was not embedded early in the design phase, and decisions such as the choice of cladding were made without a full understanding of long-term fire risks. Regulatory templates reinforced a fragmented approach, with compliance focused on isolated components rather than the building as a system. Contractual templates further exacerbated this fragmentation, as safety responsibilities were unclear and not embedded across the lifecycle. Digital templates, such as the absence of a coherent 'golden thread' of safety information, meant that critical decisions and rationales were not traceable or effectively communicated. Together, these templates created a system where safety was treated as a procedural afterthought rather than a dynamic, emergent property requiring continuous coordination. The result was a failure to anticipate and manage the complex interactions that ultimately led to the fire.

Similarly, the collapse of the Morandi Bridge highlights how systemic safety can be undermined when integration templates fail to support long-term resilience. Product templates, such as breakdown structures, focused on component-level maintenance without accounting for interaction effects or aging infrastructure. Lifecycle templates did not adequately bridge the gap between original design assumptions and evolving operational realities, leading to misaligned maintenance strategies. Regulatory oversight was periodic and reactive, lacking the systemic foresight needed to manage risks that evolve over decades. The capabilities domain was also deficient, with limited access to system safety expertise and tools capable of assessing emergent risks. These shortcomings combined to create a situation where safety degraded silently over time, culminating

Figure 1. Interaction of templates and their Influence on safety.

in a sudden and devastating collapse. In both cases, the failure was not due to a single error but to the cumulative effect of fragmented practices, misaligned priorities, and a lack of systemic coordination across the lifecycle of the built asset.

In summary, by building upon the existing concepts and topics within the literature on systems integration, this section critically examined how the established templates and practices of systems integration in construction can be problematic from a safety perspective. Figure 1 maps how five systems integration template types and their respective practices – product, lifecycle, regulatory, contractual, and digital – shape lifecycle safety outcomes. Each vertical lane represents a template category, with overlapping boundaries visually indicating their interconnected and mutually shaping nature. Horizontal bands trace identified issues through to safety consequences across the types of templates. The figure illustrates that systemic safety risks do not arise from isolated issues with distinct templates but emerge from interacting simplifications and coordination structures across the asset lifecycle. Thus, Figure 1 summarises the argument made in this section and provides the foundation for the subsequent discussion presented in Section 5 below.

5. Towards an agenda for a systems approach to safety of built assets

Thus far in the paper, we have examined the challenges introduced by current systems integration templates and practices. Building upon this, the present section consolidates those challenges and offers a structured agenda for advancing ISALS, particularly for construction professionals. The discussion of five types of templates and their associated practices – product, lifecycle, regulatory, contractual, and digital – has led to the identification of a non-exhaustive list of 23 challenges (Table 1). These challenges are grouped under three interrelated domains: conceptual orientation, practical orientation, and capabilities. Figure 2 presents these domains as overlapping spheres in a Venn diagram, reflecting the dynamic interdependencies among them and emphasising that they reinforce one another in shaping how safety is understood and addressed in construction.

The conceptual orientation (orange sphere) refers to challenges associated with the dominant ways of thinking in construction; how systems integration templates are

Table 1. A non-exhaustive list of challenges for construction professionals in achieving a systems approach to safety of built assets.

Challenges associated with conceptual orientation	Challenges associated with practical orientation	Challenges associated with capabilities
Lack of clarity and standardisation of approaches to safety	Misalignment and disconnect between system delivery and operations	Competences
Safety as a compliance issue, not a system's mission	Lack of safety considerations with a lifecycle perspective	Experience
A strong focus on 'iron triangle' for project success	Lack of appreciation of the difference between record keeping (traceability) and communication	Skills
Unclear understanding between system safety and SoS safety	Focus on minimising own risk and the adoption of blame culture	Incentives and disincentives
Working with fixed and linear structures in an evolving system	Subjective sensemaking, significance and relevance	Tailored technology that supports sensemaking, communication and decision making
System fragmentation and decomposition	Static management / lack of an adaptive view of safety	
Conflicting or competing roles, interests, and priorities across built asset lifecycle	Late safety considerations in project delivery	
Subjectivity of data, terminology, and documents	Lack of appreciation of equitable building safety	
	Fixation with risk quantification	
	Lack of attention on system design, delivery, and operation processes / major focus on an assumed understanding of the end product and its individual components	

devised, how safety is formalised, and how certain assumptions or logics gain legitimacy over others. These prevailing assumptions, often shaped by priorities like cost, time, and performance (ICE 2020; IPA 2021; Whyte and Davies 2021), tend to side-line safety as an emergent systems-level outcome. For example, while the 'iron triangle' of cost, schedule, and quality has been widely critiqued for fostering fragmentation and adversarial relationships, there remains a paucity of research on its consequences for safety planning and delivery across the lifecycle of built assets. Systems integration in construction must be fundamentally reconceptualised to place safety at its core, not as an add-on or constraint, but as a defining measure of success across the lifecycle of built assets. Such a shift can

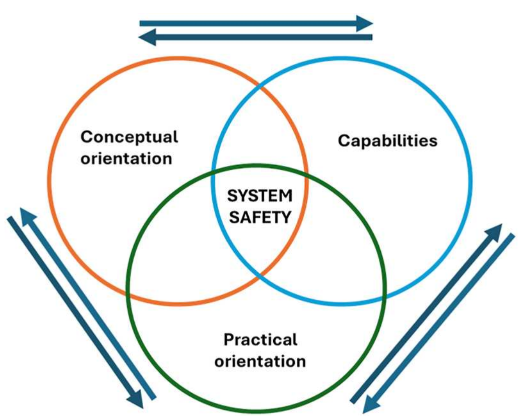

Figure 2. The three domains of challenge in achieving a systems approach to safety of built assets.

bridge persistent gaps between design, delivery, and operational phases, and support more integrated safety thinking. Moreover, this rethinking opens pathways to connect safety with broader system-level concerns – such as resilience, ecological sustainability, and just transitions – each of which also demands holistic and anticipatory approaches. Methodologically, there is also a need to understand how ideas of safety are formed, institutionalised, and acted upon. The question of how safety knowledge is created and sustained in practice, and how it shapes the behaviour of systems over time, is central to this effort.

The second domain concerns capabilities (blue sphere); the enabling structures, resources, and institutions that define the space of safety problems and solutions. At the individual level, many construction professionals are not exposed to system safety thinking or the skills required to coordinate across technical, organisational, and temporal boundaries. Existing competency frameworks and professional development practices often entrench discipline-specific views that marginalise the systemic nature of safety. At the organisational level, regulatory and procurement frameworks are not designed to support lifecycle-oriented or cross-system safety coordination. Resources such as routines, codes, contracts, and digital infrastructures often lack the interpretive and operational flexibility needed to support systemic learning, adaptation, or foresight (Çıdık and Phillips 2021). Addressing these issues demands both educational and organisational innovation. Educational programmes must better prepare professionals to engage with complexity, uncertainty, and cross-functional coordination. Likewise, institutional infrastructures – such as standards, delivery models, and oversight processes – must evolve to better reflect safety as a system-level outcome. Critically, improvements in individual and organisational capabilities must proceed together. One without the other cannot sustain the kind of change required for ISALS to take root in practice.

The third domain, practical orientation (green sphere), encompasses challenges related to how safety is enacted in the day-to-day practices of construction professionals. These practices are shaped by dominant norms, routines, and leadership models that govern how safety responsibilities are interpreted and carried out. A shift in practice toward a systems approach to safety cannot be achieved without visible and sustained leadership, both moral and professional. Those who oversee the design, delivery, and operation of built assets must embrace their ethical responsibility to prioritise human and ecological safety over short-term gains. Safety failures are not merely the result of technical or procedural breakdowns; they reflect deeper systemic and ethical shortcomings that disproportionately impact the most vulnerable. This reality demands moral leadership, leadership that places long-term wellbeing above convenience or profit, and that recognises the built environment's role in shaping societal futures. It also demands professional leadership capable of making safety everybody's duty in practice. This includes creating the institutional and cultural conditions for questioning, learning, and joint problem-solving at all levels. Without such leadership, safety risks remain fragmented and reactive, rather than being addressed as collective, dynamic, and preventable challenges. Advancing ISALS means embedding this responsibility into daily practices, project structures, and sector-wide norms.

Importantly, these domains cannot be addressed in isolation. Conceptual, practical, and capability-related challenges are mutually reinforcing and must be tackled in concert to achieve meaningful change. As shown in Figure 2, they form a complex system of influence that either constrains or enables progress toward ISALS. Ultimately, this paper proposes that enabling a systems approach to safety means rethinking safety as an emergent property, not a fixed outcome achieved by compliance, but a condition that must be continuously assured over time. This requires an iterative, evidence-driven safety assurance cycle, in which processes are continuously evaluated and adapted based on system feedback, operational experience, and evolving social and environmental conditions. This calls for a bold shift, from compliance and procedural formality to purposeful, situated action that recognises safety as a dynamic, shared, and continuous responsibility. Only through such dynamic and adaptive modes of practice can resilient, long-term safety be achieved in the conception, delivery, and operation of built assets.

6. Conclusions

The safety of built assets is a matter of critical importance, given the potentially catastrophic consequences of failures for people, ecosystems, and essential public services. Yet despite its significance, safety has often been addressed in construction research and practice through a narrow lens, primarily as a matter of technical compliance or procedural risk mitigation. This limited orientation contrasts with contemporary safety science, which understands safety as an emergent system-level outcome shaped by the complex, dynamic interactions within and between socio-technical systems. As a result, there remains a fundamental gap in how construction professionals conceive and manage safety across the lifecycle of built assets and their embeddedness in broader natural, social, and operational environments. This paper has discussed ISALS as a conceptual foundation for closing this gap. Moreover, this paper goes beyond conventional approaches to safety, such as DfS and PtD, by considering not only design interventions but also the broader factors that influence safety outcomes. It addresses skills, roles, continuity, equity, data, and regulations, all within the context of systems interaction. Rather than focusing primarily on what needs to be done or when, this paper emphasises how safety should be enacted, highlighting the complex interplay of people, processes, and technology that shapes safe outcomes.

In its current form, systems integration is predominantly shaped by delivery-oriented goals and is underpinned by simplifying templates and practices – such as breakdown structures, phase-based models, and digital records – that often reinforce compartmentalisation and limit cross-system coordination for safety. Drawing on the literature on systems integration in construction, we argue that while systems integration offers a useful lens for managing complexity and coordination, its current conceptual and practical focus is insufficient to support the integration of safety as a system-level, lifecycle-spanning concern. This paper highlights the limitations of current systems integration practices in construction and proposes ways to integrate technical, organisational, and social dimensions to co-produce safety across complex projects. By emphasising the lifecycle perspective and interactions with broader natural, built, and operational environments, this work outlines a directional concept and research agenda to inform future empirical, methodological, and policy work aimed at embedding safety into the conception, delivery, and operation of built assets.

In this paper, ISALS is not offered as a prescriptive framework, but as a directional concept, a call to rethink how safety is integrated into the conception, delivery, and operation of built assets, and how construction professionals can engage with emergent uncertainty and complexity over time. To enable such a debate, this paper identified a set of 23 interrelated challenges arising from five types of systems integration templates and associated practices: product, lifecycle, regulatory, contractual, and digital. These challenges were grouped under three intersecting domains: conceptual orientation, capabilities, and practical orientation. These domains are mutually reinforcing and must be addressed collectively to enable meaningful progress toward a systems approach. Through the discussions and suggested three domains, the paper lays a foundation for future academic, practical, and policy work aimed at repositioning safety as a dynamic, system-level outcome, one that must be continuously assured rather than reactively managed.

Future research should investigate how elements of a systems approach to built asset safety have already been partially realised in other sectors – such as rail, nuclear, and oil and gas – and assess what lessons might be transferable to the wider construction theory and practice. Empirical studies are also needed to examine how the five systems integration templates discussed in this paper shape safety coordination across project phases and system boundaries. While the present study is primarily theoretical in nature, future work could extend ISALS through empirical application. In particular, the ISALS concept could be applied to real-world cases and accidents to illustrate its practical value and demonstrate its advantages over alternative approaches to integrating safety at the systems level. Such applications would provide an opportunity to test and refine the model, further validating its relevance for analysing complex safety interactions in construction and other socio-technical systems. Moreover, further inquiry should explore how distinctions between domains such as OHS and built asset safety affect the definition of system boundaries and the development of integration strategies. Building empirical and theoretical understanding of how individual lifecycle phases and stakeholder roles contribute to or hinder the achievement of ISALS will also be essential for guiding implementation in practice.

This paper is limited by its conceptual and exploratory nature. It does not aim to provide a comprehensive empirical account or systematic review, and the challenges and domains identified are necessarily interpretive. The discussion reflects the authors' synthesis of literature across construction management, systems integration, and safety science, and is intended to open space for future dialogue, not close it. The challenge list is non-exhaustive, and the proposed concept should be seen as a starting point for further investigation rather than a finalised framework or model.

Author contributions

CRediT: **Mustafa Selçuk ÇIDIK:** Conceptualization, Writing – original draft, Writing – review & editing; **Mikela Chatzimichailidou:** Conceptualization, Writing – original draft, Writing – review & editing.

Disclosure statement

No potential conflict of interest was reported by the author(s).

References

Allocco, M. 2010. "Safety Analyses of Complex Systems: Considerations of Software, Firmware, Hardware, Human, and the Environment".

Barua, S., X. Gao, and M. S. Mannan. 2016. "Comparison of Prescriptive and Performance-Based Regulatory Regimes in the USA and the UK." *Journal of Loss Prevention in the Process Industries* 44:764–769. https://doi.org/10.1016/j.jlp.2016.10.009.

Bijker, W. E., T. P. Hughes, and T. J. Pinch. 1987. *The Social Construction of Technological Systems: New Directions in the Sociology and History of Technology*. Cambridge, MA: MIT Press.

Bosher, L. 2008. *Hazards and the Built Environment: Attaining Built-in Resilience*. New York: Routledge.

Brady, T., and A. Davies. 2014. "Managing Structural and Dynamic Complexity: A Tale of Two Projects." *Project Management Journal* 45 (4): 21–38.

Brusoni, S., and A. Prencipe. 2001. "Unpacking the Black Box of Modularity: Technologies, Products and Organizations." *Industrial and Corporate Change* 10 (1): 179–205. https://doi.org/10.1093/icc/10.1.179.

BSRIA (Building Services Research and Intelligence Association). 2018. *BG 54/2018: Soft Landings Framework 2018*. https://www.bsria.com/uk/product/QnPd6n/soft_landings_framework_2018_bg_542018_a15d25e1/?srsltid=AfmBOorNZ1L-6inHHuybzEbYEPSyVGZqAov4IjjSUbnx0ei-4LcNbsb1.

Chan, A. P., D. W. Chan, and J. F. Yeung. 2009. *Relational Contracting for Construction Excellence: Principles, Practices and Case Studies*. London: Routledge.

Chatzimichailidou, M., and Y. Ma. 2022. "Using BIM in the Safety Risk Management of Modular Construction." *Safety Science* 154:105852. https://doi.org/10.1016/j.ssci.2022.105852.

Chatzimichailidou, M., T. Whitcher, and N. Suzic. 2024. "Complementarity and Compatibility of Systems Integration and Building Information Management." *IEEE Systems Journal* 18 (2): 1198–1207. https://doi.org/10.1109/JSYST.2024.3387064.

Çıdık, M. S., and D. Boyd. 2022. "Value Implication of Digital Transformation: The Impact of the Commodification of Information." *Construction Management and Economics* 40 (11–12): 903–917. https://doi.org/10.1080/01446193.2022.2033287.

Çıdık, M. S., D. Boyd, and N. Thurairajah. 2017. "Ordering in Disguise: Digital Integration in Built-Environment Practices." *Building Research & Information* 45 (6): 665–680. https://doi.org/10.1080/09613218.2017.1309767.

Çıdık, M. S., and S. Phillips. 2021. "Buildings as Complex Systems: The Impact of Organisational Culture on Building Safety." *Construction Management and Economics* 39 (12): 972–987. https://doi.org/10.1080/01446193.2021.1966816.

Dekker, S., P. Cilliers, and J. H. Hofmeyr. 2011. "The Complexity of Failure: Implications of Complexity Theory for Safety Investigations." *Safety Science* 49 (6): 939–945. https://doi.org/10.1016/j.ssci.2011.01.008.

Denicol, J., A. Davies, and I. Krystallis. 2020. "What are the Causes and Cures of Poor Megaproject Performance?" *A Systematic Literature Review and Research Agenda. Project Management Journal* 51 (3): 328–345.

Dunn, S., and S. Gonzalez-Otalora. 2021. "Development of an Adaptive Solution to Increase Infrastructure System Resilience Based Upon a Location-Allocation Methodology." *Journal of Infrastructure Systems* 27 (1): 04020043. https://doi.org/10.1061/(ASCE)IS.1943-555X.0000585.

Flyvbjerg, B. 2017. *Introduction: The Iron law of Megaproject Management*, 1–18. Oxford: Bent Flyvbjerg.

Frigant, V., and D. Talbot. 2005. "Technological Determinism and Modularity: Lessons from a Comparison between Aircraft and Auto Industries in Europe." *Industry and Innovation* 12 (3): 337–355. https://doi.org/10.1080/13662710500195934.

Hackitt, J. 2018. "Building a Safer Future." *Independent Review of Building Regulations and Fire Safety: Final Report* 5–12. https://assets.publishing.service.gov.uk/media/5afc50c840f0b622e4844ab4/Building_a_Safer_Future_-_web.pdf.

Health and Safety Executive. 2015. *Managing Health and Safety in Construction: Construction (Design and Management) Regulations 2015*. Guidance on Regulations (L153). HSE Books. https://www.hse.gov.uk/pubns/books/l153.htm.

Henderson, R. M., and K. B. Clark. 1990. "Architectural Innovation: The Reconfiguration of Existing Product Technologies and the Failure of Established Firms." *Administrative Science Quarterly* 35 (1): 9–30. https://doi.org/10.2307/2393549.

Hernández, J. R. E., S. T. Moghadam, and P. Lombardi. 2024. "Urban Sustainability in Social Housing Environments: A Spatial Impact Assessment in Bogotá, Colombia." *Cities* 154:105392. https://doi.org/10.1016/j.cities.2024.105392.

Ibrahim, C. K. I. C., P. Manu, S. Belayutham, A. M. Mahamadu, and M. F. Antwi-Afari. 2022. "Design for Safety (DfS) Practice in Construction Engineering and Management Research: A Review of Current Trends and Future Directions." *Journal of Building Engineering* 52:104352. https://doi.org/10.1016/j.jobe.2022.104352.

ICE (Institution of Civil Engineers). 2020. *A Systems Approach to Infrastructure Delivery: A Review of How Systems Thinking Can Be Used to Improve the Delivery of Complex Infrastructure Projects*. ICE: London.

IPA (Infrastructure and Projects Authority. 2021. *Project Routemap: Systems Integration*. London: UK Government.

ISO/IEC/IEEE (International Organisation for Standardisation / International Electrotechnical Commissions / Institute of Electrical and Electronics Engineers). 2015. *ISO/IEC/IEEE 15288 Systems and Software Engineering – System Life Cycle Processes*. Geneva, Switzerland: ISO (International Organization for Standardization).

Jasanoff, S. 2004. "The Idiom of Co-production." In *States of Knowledge*, 1–12. Routledge. https://www.taylorfrancis.com/chapters/edit/10.4324/9780203413845-1/idiom-co-production-sheila-jasanoff.

Johnson, S. B. 1997. "Three Approaches to Big Technology: Operations Research, Systems Engineering, and Project Management." *Technology and Culture* 38 (4): 891–919. https://doi.org/10.1353/tech.1997.0005.

Kordi, N. E., S. Belayutham, and C. K. I. Che Ibrahim. 2021. "Mapping of Social Sustainability Attributes to Stakeholders' Involvement in Construction Project Life Cycle." *Construction Management and Economics* 39 (6): 513–532. https://doi.org/10.1080/01446193.2021.1923767.

Koskela, L. 2008. "Is a Theory of the Built Environment Needed?" *Building Research & Information* 36 (3): 211–215. https://doi.org/10.1080/09613210801936530.

Lenfle, S., and C. Loch. 2010. "Lost Roots: How Project Management Came to Emphasize Control over Flexibility and Novelty." *California Management Review* 53 (1): 32–55. https://doi.org/10.1525/cmr.2010.53.1.32.

Leveson, N. G. 2016. *Engineering a Safer World: Systems Thinking Applied to Safety*, 560. Cambridge, MA: The MIT Press.

Locatelli, G., M. Mancini, and E. Romano. 2014. "Systems Engineering to Improve the Governance in Complex Project Environments." *International Journal of Project Management* 32 (8): 1395–1410. https://doi.org/10.1016/j.ijproman.2013.10.007.

Mahnken, T. G. 2008. *Technology and the American way of war*. New York, NY: Columbia University Press.

McGivern, G., S. Dopson, E. Ferlie, M. Fischer, L. Fitzgerald, J. Ledger, and C. Bennett. 2018. "The Silent Politics of Temporal Work: A Case Study of a Management Consultancy Project to Redesign Public Health Care." *Organization Studies* 39 (8): 1007–1030. https://doi.org/10.1177/0170840617708004.

Meacham, B. J., and I. J. van Straalen. 2018. "A Socio-Technical System Framework for Risk-Informed Performance-Based Building Regulation." *Building Research & Information* 46 (4): 444–462. https://doi.org/10.1080/09613218.2017.1299525.

Mêda, P., H. Sousa, and E. Hjelseth. 2020. "Data Templates-Product Information Management Across Project Life-Cycle." In *Sustainable Materials in Building Construction* (pp. 117–133). Cham: Springer International Publishing.

Mosey, D. 2009. *Early Contractor Involvement in Building Procurement: Contracts, Partnering and Project Management*. Chichester: John Wiley & Sons.

Murtagh, N., L. Scott, and J. Fan. 2020. "Sustainable and Resilient Construction: Current Status and Future Challenges." *Journal of Cleaner Production* 268:122264. https://doi.org/10.1016/j.jclepro.2020.122264.

Noktehdan, M., M. Shahbazpour, M. R. Zare, and S. Wilkinson. 2019. "Innovation Management and Construction Phases in Infrastructure Projects." *Journal of Construction Engineering and Management* 145 (2): 04018135. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001608.

Oginni, D., F. Camelia, M. Chatzimichailidou, and T. L. Ferris. 2023. "Applying System-Theoretic Process Analysis (STPA)-Based Methodology Supported by Systems Engineering Models to a UK Rail Project." *Safety Science* 167:106275. https://doi.org/10.1016/j.ssci.2023.106275.

Orlikowski, W. J., and J. Yates. 2002. "It's about Time: Temporal Structuring in Organizations." *Organization Science* 13 (6): 684–700. https://doi.org/10.1287/orsc.13.6.684.501.

Patriarca, R., J. Bergström, G. Di Gravio, and F. Costantino. 2018. "Resilience Engineering: Current Status of the Research and Future Challenges." *Safety Science* 102:79–100. https://doi.org/10.1016/j.ssci.2017.10.005.

Perrow, C. 1984. *Normal Accidents*. New York: Basic Books.

Rasmussen, J. 1997. "Risk Management in a Dynamic Society: A Modelling Problem." *Safety Science* 27 (2-3): 183–213. https://doi.org/10.1016/S0925-7535(97)00052-0.

Reason, J. 1997. *Managing the Risks of Organizational Accidents*. Abingdon, Oxfordshire: Routledge. https://www.taylorfrancis.com/books/mono/10.4324/9781315543543/managing-risks-organizational-accidents-james-reason.

RSSB (Rail Safety and Standards Board). 2023. *Generic Hazard List*. https://www.rssb.co.uk/safety-and-health/common-solutions/risk-and-safety-intelligence/safety-management-resources/generic-hazard-list.

Samsudin, N. S., M. Z. Mohammad, N. Khalil, N. D. Nadzri, and C. K. I. C. Ibrahim. 2022. "A Thematic Review on Prevention through Design (PtD) Concept Application in the Construction Industry of Developing Countries." *Safety Science* 148:105640. https://doi.org/10.1016/j.ssci.2021.105640.

Schulte, P. A., R. Rinehart, A. Okun, C. L. Geraci, and D. S. Heidel. 2008. "National Prevention through Design (PtD) Initiative." *Journal of Safety Research* 39 (2): 115–121. https://doi.org/10.1016/j.jsr.2008.02.021.

SEBoK Editorial Board. 2021. *The Guide to the Systems Engineering Body of Knowledge (SEBoK)*, v. 2.5, R.J. Cloutier (Editor in Chief). Hoboken, NJ.

Shenhar, A. J., and D. Dvir. 2007. *Reinventing Project Management: The Diamond Approach to Successful Growth and Innovation*. Boston, MA: Harvard Business Review Press.

Sherratt, F., and C. Ivory. 2019. "Managing 'a Little bit Unsafe': Complexity, Construction Safety and Situational Self-organising." *Engineering, Construction and Architectural Management* 26 (11): 2519–2534. https://doi.org/10.1108/ECAM-09-2018-0376.

Spinardi, G., and A. Law. 2019. "Beyond the Stable Door: Hackitt and the Future of Fire Safety Regulation in the UK." *Fire Safety Journal* 109:102856. https://doi.org/10.1016/j.firesaf.2019.102856.

Sull, D. N., and K. M. Eisenhardt. 2015. *Simple Rules: How to Thrive in a Complex World*. Boston, MA: Houghton Mifflin Harcourt.

Watson, M. D. 2019. "Systems Engineering Principles and Hypotheses." *Insight* 22 (1): 18–28. https://doi.org/10.1002/inst.12233.

Whyte, J. 2016. "The Future of Systems Integration within Civil Infrastructure: A Review and Directions for Research." In *INCOSE International Symposium*. Vol. 26, 1541–1555. https://incose.onlinelibrary.wiley.com/doi/abs/10.1002/j.2334-5837.2016.00244.x.

Whyte, J. 2018. "Systems Engineering and the Project Delivery Process in the Design and Construction of Built Infrastructure".

Whyte, J., and A. Davies. 2021. "Reframing Systems Integration: A Process Perspective on Projects." *Project Management Journal* 52 (3): 237–249. https://doi.org/10.1177/8756972821992246.

Whyte, J., A. Davies, and C. Sexton. 2022. "Systems Integration in Infrastructure Projects: Seven Lessons from Crossrail." *Proceedings of the Institution of Civil Engineers-Management, Procurement and Law* 175 (3): 103–109. https://doi.org/10.1680/jmapl.21.00014.

Whyte, J., A. Stasis, and C. Lindkvist. 2016. "Managing Change in the Delivery of Complex Projects: Configuration Management, Asset Information and 'Big Data'." *International Journal of Project Management* 34 (2): 339–351. https://doi.org/10.1016/j.ijproman.2015.02.006.

Winch, G. M. 2006. "Towards a Theory of Construction as Production by Projects." *Building Research & Information* 34 (2): 154–163. https://doi.org/10.1080/09613210500491472.
Woods, D. D. 2015. "Four Concepts for Resilience and the Implications for the Future of Resilience Engineering." *Reliability Engineering & System Safety* 141:5–9. https://doi.org/10.1016/j.ress.2015.03.018.