Enhancing Fire and Life Safety Resilience of Critical Infrastructure in Saudi Arabia: A Risk-Based Engineering Framework for Vision 2030

Abstract:

The fact that Saudi Arabia is concentrating on developing and modernising its transport, energy, utility, healthcare, digital, and high-occupancy facilities means that fire and life safety have to be taken into account if continuous operation is to be maintained and regulatory requirements are to be met. This study presents a risk-based engineering method designed to enhance the fire resistance of important infrastructure as part of Vision 2030. In order to obtain peer-reviewed, reliable evidence published between 2020 and 2025, a structured critical review was conducted using the PRISMA method. The evidence was examined in six closely related areas: the definition of hazard and scenario; passive and active protection; life safety and evacuation; emergency response; functional continuity and recovery; and digital intelligence and governance. Existing research shows that mere compliance with codes is not enough; resilience demands the selection of credible scenarios, an understanding of how the various systems interact, taking human reliability into account, having an effective emergency command structure, setting clearly defined recovery objectives, and being able to learn from operational data. Research carried out in Saudi Arabia also points out the advantages of carrying out structured risk assessments and maintaining consistent fire-safety evaluations, even though the 2024 Saudi codes provide a solid prescriptive basis for alarms, suppression, smoke control, egress, and responder access. The proposed framework therefore combines adherence to the code with factors such as the criticality of assets, probabilistic scenario analysis, performance objectives, verification, resilience indicators, and lifecycle assurance. The approach so developed is intended for owners, regulators, designers, and operators who wish to protect lives, minimise the risk of cascading disruptions, and quickly restore key services. It also includes a research programme to verify the findings in the Saudi context by making use of incident data, full-scale testing, digital twins, and information on recovery time.

1. Introduction

It is different from ordinary property in that the consequences of a failure extend beyond the damage suffered by the asset itself. For example, a fire in a transport tunnel can disrupt mobility and stop emergency services from getting to the area; a fire in an energy or utility facility can cause other services that rely on it to cease working; a fire in a hospital can result in a loss of treatment capacity exactly when such treatment is most needed; and a fire in a small data or telecommunications facility can still have wide-ranging operational consequences. Because of this, current resilience research treats infrastructure as a networked system in which performance is based on robustness—that is, the ability to absorb shocks—adaptation, and recovery, rather than simply on resistance (Mottahedi et al., 2021; Sathurshan et al., 2022). This change in perspective is important for fire safety since traditional compliance usually concentrates on preventing ignition, containing the fire and smoke, and enabling people to evacuate. At the same time, critical infrastructure also has to ensure that essential functions continue and must have a plan for returning to normal service.

The importance of fire resilience lies in the fact that it relates to both public safety and the continued operation of a building. As Himoto (2021) points out, fire resilience involves the loss of a building's functionality and its subsequent recovery, and Himoto and Suzuki (2021) showed that fire-hazard modelling, the vulnerability of various components, the reliability of the protection systems, and the recovery time can all be combined by means of computational methods. Further research has indicated that even if a fire is successfully put out, water damage may still take place and thus can delay the restoration of functionality; this demonstrates that a robust assessment must consider secondary effects and should not confine itself to the mere extinction of the fire (Himoto et al., 2024). The key engineering question is therefore not just whether the occupants can escape from a design fire, but whether the asset can anticipate realistic events, prevent the situation from getting worse, maintain tenable conditions, help the responders, contain both physical and operational losses, and restore the necessary services within an acceptable time frame.

The situation is especially serious in Saudi Arabia. Studies into fire safety in the country have demonstrated the actual advantages of carrying out structured risk assessments in workplace facilities and of having clearly defined fire safety management systems in schools (Hassanain et

al., 2022a; Hassanain et al., 2022b). A model of the analytic hierarchy process which was developed in Saudi Arabia also illustrates the benefits of taking into account hazards, user behaviour, access, emergency design, and protective actions as part of a coherent assessment process (Alfalah et al., 2023). At the regulatory level, both the Saudi Fire Protection Code and the Saudi General Building Code contain specific requirements relating to life-safety systems, fire alarm and detection, automatic suppression, smoke control, means of egress, fire-command functions and access for emergency responders (Saudi Building Code National Committee, 2024a, 2024b). The Saudi Central Bank has similarly strongly emphasized the need to apply the Civil Defence requirements and the Saudi Building Code for preventive fire protection in regulated institutions (Saudi Central Bank, 2023).

The policy environment is also a significant factor. According to Saudi Vision 2030 (2024), national transformation is connected with infrastructure delivery, quality of life, digitalisation, investment and institutional performance; since these objectives increase the value of continuous infrastructure services they also lead to ever more complex assets in which architectural innovation, automation, renewable-energy systems, batteries, data platforms and interconnected operations might affect fire risk. International research has also shown that sustainability, smartness and fire resilience can support one another but may at the same time come into conflict when new materials or technologies introduce previously unrecognised hazards (McNamee and Meacham, 2025; Barua et al., 2025). Which is why it is necessary to adopt a risk-based approach in order to link the code-compliance baseline to consequence, criticality and recovery.

The existing literature is still in a fragmented state. While research concerning tunnels offers a detailed understanding of smoke, ventilation, suppression, and prediction, it usually concentrates on one kind of infrastructure only (Lombardi et al., 2023). With regard to smart firefighting, the studies combine detectors and artificial intelligence, but they place a greater focus on forecasting events than on institutional assurance (Khan et al., 2022). Even though the models developed to enhance the fire resistance of buildings do include considerations of recovery, they were not designed to take into account the interdependencies between the various elements of Saudi infrastructure. Although assessments in Saudi Arabia have become more consistent, a comprehensive resilience framework that covers design, operation, emergency response, and restoration has still not been set up. In order to address this gap, the present review brings

together the latest evidence into an engineering framework which can be used to guide decisions concerning critical infrastructure in the Kingdom.

2. Aim, Objectives and Review Questions

The review has been prepared by incorporating evidence gathered between 2020 and 2025 into an engineering framework for application in Saudi Arabia, with fire safety and life safety considered as one area concerned with protection, emergency performance, and service continuity. Different from earlier reviews which had simply listed fire tests or evaluated various emergency-response factors separately, the current study looks at how different types of evidence can support decision-making at each stage of an infrastructure's lifecycle.

The review has five aims: the first is to identify the main factors which contribute to fire and life-safety risks in various types of critical infrastructure at all stages of their lifecycle; the second involves finding out how the prescriptive requirements of Saudi Arabia can be supplemented by performance and risk-based testing methods; the third is to integrate the technical, organisational, human and digital capabilities that affect the ability to contain losses and to carry out recovery; the fourth is to develop a practical decision-making pathway and indicators of robustness for the owners, regulators, designers and operators; and the fifth consists in establishing the research priorities that require Saudi-specific data or validation. The following four review questions are then looked at: What features cause fire risk in critical infrastructure to differ so much from that in ordinary buildings? Which combinations of preventive, protective, response and recovery measures provide the best support for resilience? How should uncertainty and the interactions inside systems be taken into account in engineering assurance? And what governance and digital capabilities are needed to bring the framework in line with Vision 2030?

3. Methodology

The review was based on a structured critical approach in accordance with the PRISMA guidelines, as the subject matter involves experimental fire science, computational modelling, risk and resilience theory, facility-management studies, digital technologies, national codes, and

policy. A conventional meta-analysis is not suitable in this case since the outcome measures vary: while some studies supply data on heat release rate, smoke temperature, or critical velocity, others concentrate on recovery time, rank risk factors, assess management practices, or suggest conceptual frameworks. In order to ensure transparency, the search and eligibility criteria complied with both PRISMA 2020 and PRISMA-S. The time frame for the evidence was set from 2020 to 2025 in order to correspond with the current area of focus and to include the most recent developments in resilience engineering, artificial intelligence, and Saudi regulations.

The search queries for Scopus and the Web of Science were grouped into four categories of concepts: fire safety, life safety and fire resilience; critical infrastructure, together with buildings, tunnels, utilities and industrial facilities; risk-based approaches, performance-resilience and emergency response; and digital twin technology, artificial intelligence and smart firefighting where applicable. There was also a separate section concerned with the Saudi context, this consisting of the use of the terms Saudi Arabia, KSA, Riyadh, Jeddah or Makkah. When carrying out the searches, the official Saudi sources referred to were the 2024 building and fire codes, the 2023 SAMA fire-protection circular, and the Vision 2030 annual report. In order to identify relevant methods and source studies, backwards and forward snowballing was carried out on the two model papers provided.

It had to be in English, have been carried out from 2020 to 2025, and include evidence that could be used when making fire and life-safety decisions at an infrastructure level. The studies included in the review were peer-reviewed reviews, experiments, simulations, risk models, digital-fire studies, and those based on the Saudi situation. We also included official Saudi codes and policy documents that either directly dealt with or defined the problem. Studies that concerned themselves only with wildfires, tests that involved nothing but the combustion of materials without any reference to infrastructure, papers that did not give a clear account of their methodology, and those outside the date range were excluded. Residential research was only included if the method dealt with system-level risk resilience and/or smart-fire management in a manner applicable to critical facilities. The final body of evidence consists of the 30 references mentioned in this paper; the aim was to develop a framework rather than to carry out an exhaustive bibliometric count.

In order to carry out the data extraction, an organised matrix was used, including spaces for the type of infrastructure, the hazard or scenario, the study method, the safety function, the performance measure, the way in which uncertainty was handled, the human or organisational factor, the consequences for recovery, digital capability and Saudi transferability; the evidence was then deductively assigned to six resilience areas, namely: (1) the definition of hazard and scenario; (2) passive and active protection; (3) life safety and evacuation; (4) emergency response; (5) continuity and recovery; and (6) digital intelligence and governance. Inductive coding was subsequently performed in order to identify recurring problems throughout various domains such as interactions between protection systems, data quality, maintenance, information for responders, sustainability trade-offs, and secondary damage.

The evaluation employed five practical criteria, which were assessed qualitatively as being either strong, moderate, or limited: methodological transparency, relevance to fire or life safety, evidence of validation, the way in which uncertainty was dealt with, and the extent of transferability to complex infrastructure. Since there is no validated scale that can be applied to all of the study designs included in the review, a numerical quality score was not used to rank the authors or the journals; instead, stronger evidence was given more weight when interpreting the results, and conceptual studies were employed to identify relationships rather than to provide quantified effects. The process of synthesis consisted of comparing the findings that were convergent, spotting any contradictions, separating out the code requirements from the suggested improvements, and then converting the resulting themes into a lifecycle decision framework. Figure 1 gives a summary of the process from review to framework, and Table 1 contains the review protocol.

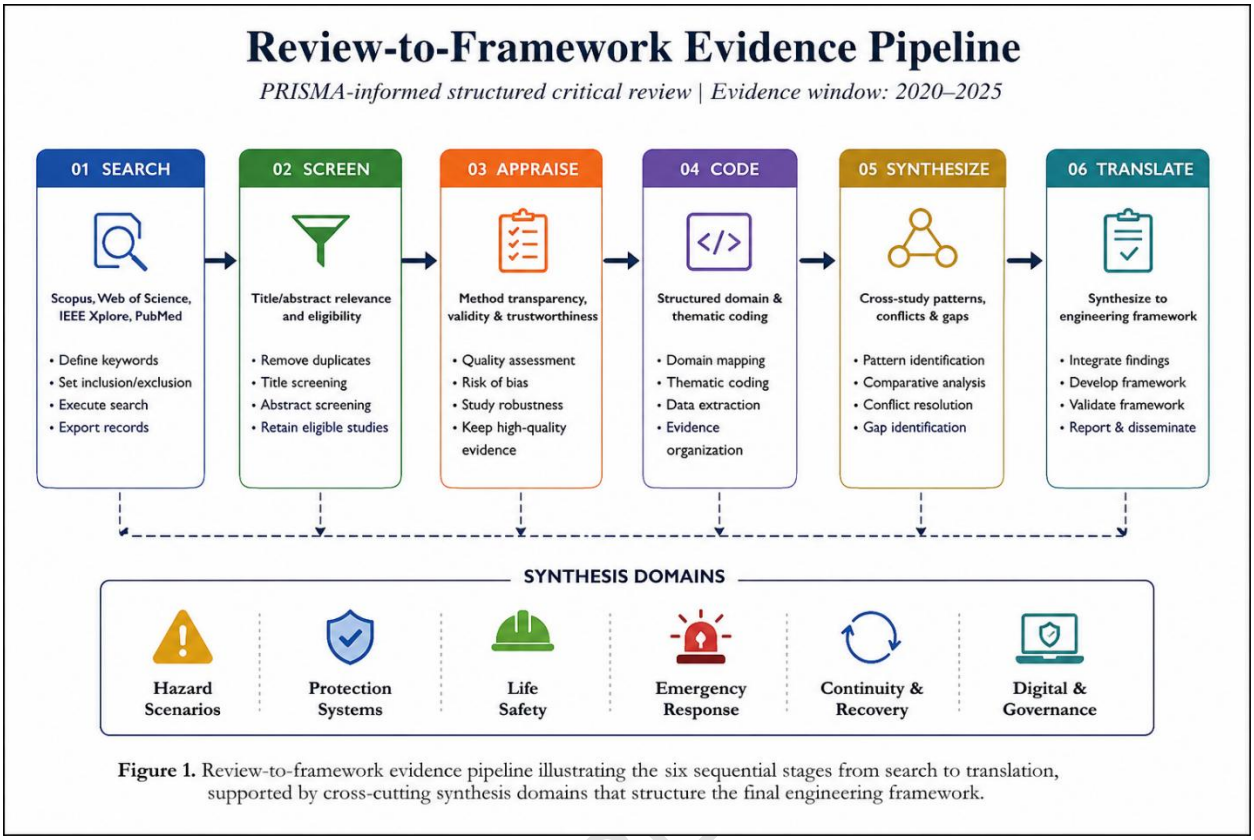

Figure 1. Review-to-framework evidence pipeline illustrating the six sequential stages from search to translation, supported by cross-cutting synthesis domains that structure the final engineering framework.

Figure 1. Review-to-framework evidence pipeline

Table 1. Review protocol and evidence-synthesis criteria.

Review element	Specification
Review design	PRISMA-informed structured critical review with qualitative framework synthesis.
Evidence period	2020-2025 only for cited evidence.
Core databases	Scopus and Web of Science Core Collection; targeted official Saudi sources.
Main concepts	Fire/life safety; critical infrastructure; resilience; risk/performance-based engineering; emergency response; digital fire intelligence.
Included evidence	Peer-reviewed reviews, experiments, simulations, risk models, digital-fire studies, Saudi case studies, and directly relevant Saudi codes/policy.
Key exclusions	Pre-2020 or post-2025 evidence; wildfire-only studies; material tests without infrastructure implications; inaccessible methodological detail.
Synthesis domains	Hazard scenarios; protection systems; life safety; emergency response; continuity/recovery; digital intelligence/governance.
Quality lens	Method transparency, fire-safety relevance, validation, uncertainty treatment, and transferability.
Final corpus	30 sources reported in the reference list; heterogeneous outcomes synthesised qualitatively rather than pooled statistically.

4. Evidence Synthesis

4.1 Risk, severity and the significance of fire resilience

In the literature, resilience is regarded as being different from simple robustness. Mottahedi and other authors (2021) define resilient critical infrastructure by mentioning anticipation, protection, absorption, adaptation and recovery, while Sathurshan and his co-authors (2022) emphasize the use of performance indicators at the pre-event, during-event and post-event stages. Models that have been specifically developed for fires go even further by linking physical damage with performance over time (Himoto, 2021). Resilience must therefore, in the case of a key asset in Saudi Arabia, be seen as the capacity to keep the effects of a fire occurring within acceptable life-safety limits, to prevent a serious loss of essential functions, to permit safe emergency intervention and to restore the priority services in accordance with the recovery objectives approved by the owner and the authority.

The definition changes the starting point of the design process in that the first step should be to evaluate the criticality of the assets rather than selecting a fire protection system. Before considering different scenarios, engineers must establish which services are essential, identify the dependencies, examine the plausible maximum outages, take into account the populations at risk, and define recovery constraints. Although a hospital emergency department, a metro interchange, a fuel-processing unit, and a data centre all satisfy the minimum requirements set out in the codes, the amount of downtime they can tolerate and the degree of damage they can withstand will be very different. Risk-based engineering can show this difference by combining the probability of a scenario with the system's conditional performance and the consequences. The objective is not to replace deterministic safety measures with uncertain probabilities; rather, it is to make use of structured uncertainty in order to demonstrate that the prescriptive minimums might be inadequate for assets which have serious consequences.

The literature also cautions against viewing resilience as a single, independent value separate from the engineering mechanisms. Himoto and Suzuki (2021) show that both damage and recovery are affected by a variety of factors, including component vulnerability, detection, suppression, the actions of the occupants, and the fire service's response. Similarly, Frantzich et al. (2025) adopt a comparable method by employing a decision-support framework to balance a number of fire-resilience characteristics rather than relying on a single protective measure. The resilience index for Saudi critical infrastructure should therefore be decomposable so that

decision-makers can determine whether the weakness stems from ignition control, compartmentation, smoke management, evacuation, responder access, redundancy, recovery resources, or governance. A transparent dashboard is more defensible than an opaque overall score.

4.2 Scenario engineering, the interaction between protection systems and life safety

We should first explain what is meant by a scenario since the complicated nature of the infrastructure causes fire conditions that are not standard. Studies concerning tunnels have revealed that the movement of smoke is strongly affected by ventilation, the geometry of the tunnel, the presence of more than one fire source, and the application of suppression measures. Tang et al. (2020) found that the critical ventilation velocity for two fires situated close to one another depends on the distance between them and the rate at which heat is released. Liu et al. (2021) discovered that both water mist and longitudinal ventilation act in a non-linear manner, meaning that even if each individual system is advantageous on its own, their combination does not always lead to an optimal overall result. Wang et al. (2021), by using CFD, reached a similar conclusion, showing that the ventilation strategy and the location of the fire have a significant impact on the conditions in underground utility tunnels. These results support the general view that resilience should be assessed by testing the interactions between systems in realistic combined scenarios rather than by examining each subsystem in isolation.

This principle also applies to buildings and industrial facilities; passive fire resistance, compartmentation and the protection of openings all contribute to containing the spread of fire and provide the required time for evacuation as well as for emergency response to occur; active systems have the role of detecting the fire, sounding the alarm, putting it out and managing the smoke; the structural systems must keep their stability for the designated period; and the means of egress have to remain usable under realistic conditions that include both the occupants and the smoke. According to the Saudi Fire Protection Code, the minimum mandatory requirements for fire alarms, automatic sprinkler systems, alternative extinguishing systems, standpipes, smoke control, fire-department connections, fire command centres and responder radio coverage are established, while the Saudi General Building Code deals with issues relating regarding occupancy, high-rise buildings, underground buildings, hazardous materials, fire resistance and means of egress (Saudi Building Code National Committee, 2024a, 2024b). A durability

framework should not reduce these requirements; it should instead take into account the additional verification that is justified by the facility's criticality.

The examples from Saudi Arabia show the benefits of such verification. In the study (2022a), Hassanain used a case study to prove that a systematic risk assessment can identify not only physical hazards but also flaws in behaviour and management. In their other study (2022b), Hassanain et al. developed a fire-safety management framework for schools and said that administrative and operational controls must complement the existing systems. Alfalah et al. (2023) proposed a model for assessing buildings in Saudi Arabia that combines hazard and safety factors using AHP in order to improve consistency and traceability. Together, these studies suggest that fire safety should be managed as a layered system because its reliability depends on design, inspection, maintenance and user behaviour.

As far as safety is concerned, care needs to be taken regarding uncertainty. It is true that each of the assumptions about response time, mobility, staffing, the condition of the doors, the rate at which the fire spreads, the effectiveness of the alarms, and the availability of escape routes may be reasonable individually, yet an unsafe situation can still arise when all of these assumptions are taken into account. Although probabilistic methods can illustrate how these factors are connected, Bjelland and Njå (2022) warn that probabilistic verification has only limited value if the assumptions, the uncertainty, and the performance criteria are not clearly defined. Scenario sets for critical assets should therefore include normal design conditions, plausible degraded states, and a number of extreme but credible cases such as delayed detection, impaired suppression, blocked egress, loss of normal power, failure of the smoke control system, high visitor density, a maintenance outage, or simultaneous operational disturbances. The objective is to identify cliff-edge behaviour and to enhance graceful degradation.

4.3 Emergency Response, Organisational Reliability and Recovery

Emergency response ought to be seen as a matter of durability rather than as something that is dealt with after an event has occurred. Research concerning smart firefighting illustrates the dangers that responders encounter when they go into an area while people are still being evacuated and stresses the advantages of critical-event libraries, real-time information, and decision trees for incident command (Khan et al., 2022). Likewise, studies focused on infrastructure robustness stress the importance of coordination, risk awareness, warnings,

preparedness, and recovery. Abudu et al. (2025) point out the repeated weaknesses in the emergency-response infrastructure, for example, the lack of coordinated action and the limitations of resources, and therefore argue that it is important to combine technical capability with institutional preparedness rather than treating these as separate programmes.

With regard to critical infrastructure, just as much attention should be given to the organisation's reliability as to its physical protection. The operating model should indicate who is responsible for alarms, specify the thresholds at which escalation is required, name the individuals who have the authority to shut down systems, define all the various command roles, describe how it co-ordinates with Civil Defense, take into account the situation in which the systems are impaired, make sure that emergency communications stay operational, set out the responsibilities of contractors and establish the criteria for re-entry. The drills should focus on the quality of the decisions and on the way in which information flows rather than merely on evacuation time. Changes to shift patterns, language diversity, accessibility requirements and the number of trained operators can affect performance if a real incident takes place. The framework therefore treats competency, exercises, maintenance governance and emergency command as engineered barriers, each with measurable assurance requirements.

Recovery should also begin before a fire occurs. According to the functional continuity models, restoration depends not only on the degree of direct damage but also on the time required to replace the components, reinstate the utilities, ensure that safety has been restored, and obtain operational approval (Himoto, 2021; Himoto et al., 2024). For critical assets, it is necessary to set recovery-time objectives for key functions, identify any single points of failure, pre-plan alternative service modes, protect the spares and documentation, and define criteria for a phased restart. In addition to taking account of structural loss, attention should be paid to the quantity of suppression water used, the level of smoke contamination, and the damage to sensitive equipment. As a result, fire planning carried out afterwards changes from being a simple insurance exercise to becoming a design input.

4.4 Digital intelligence: progressing from detection to predictive fire operations

Recent research on digital-fire methods has now made it possible to transition from reactive alarm systems to predictive ones. In their 2022 study, Zhang and his colleagues used two agents to train a deep-learning model on a numerical tunnel-fire database which had been verified and

were able to predict changes in the size, position and temperature field of the fire over a short period of time. Ahn and his co-workers (2024) employed machine-learning ensembles to classify the risk of a building fire on the basis of a number of building and contextual variables. Chen and others (2024) combined computer vision, compliance logic and generative techniques in order to assess and redesign building blueprints. The studies thus demonstrate three different digital functions: pre-incident risk screening, evaluation at the design stage and forecasting during an incident.

The highest level of resilience is obtained by combining sensors, models, and a digital model of the asset. Xie and others in 2025 created a digital twin of a building using AIoT technology which is able to reconstruct fire conditions from sensor data. On the other hand, Wang and colleagues in 2025 developed an application that allows for the real-time detection, segmentation, measurement, and estimation of heat release. Such technologies could assist in the protection of important assets in Saudi Arabia by providing incident commanders with hazard information that is specific to a location, helping operators to identify situations that are worsening, and allowing learning following an event. Yet they should be used to supplement, not to replace, certified detection, suppression, communication, and human command.

Digital resilience may also give rise to new kinds of failure. The accuracy of the predictions is completely dependent on the way the sensors are arranged, on their calibration, on the communication systems, on the validity of the model, and on the quality of the training data. If automated recommendations are used when making decisions, then aspects such as cybersecurity, the continuity of the power supply, data integrity, and the interfaces become just as important as fire safety. McNamee and Meacham (2025), together with Baru et al. (2025), cautions that smart technology could cause unanticipated fire hazards if the various interactions are not carefully evaluated. The framework therefore requires that digital functions have clearly defined safety roles, supporting evidence, fallback possibilities, and monitoring of data quality and uncertainty that is understandable to humans. A complex model without a reliable operational interface can in fact decrease rather than increase resilience.

4.5 Saudi Regulatory and Vision 2030 Compliance

The resilience-based approach can be taken since the Saudi regulatory framework includes sufficient detail. SBC 801-CR-2024 sets out rules concerning the prevention of operational fires,

access for firefighting vehicles, water supplies, fire command centres, radio coverage for the responders, and fire-protection systems. Furthermore, SBC 201-CR-2024 specifies building classification, the special occupancy requirements, fire-resistance measures, and the means of egress (Saudi Building Code National, 2024a, 2024b). The 2023 SAMA circular states that regulated defence organisations must implement the provisions of the Civil Defence and comply with the requirements of the Saudi Building Code, considering fire protection as a mandatory element of facility practice (Saudi Central Bank, 2023).

The two-stage assurance model which has been suggested includes a compliance stage and an improvement stage. During the first stage it is necessary to adhere to all applicable Saudi regulations, satisfy Civil Defence requirements and follow the rules that are specific to the sector in question. In the second stage, enhancement is carried out on the basis of criticality: the asset owner and the authorities responsible for giving approval must determine whether a loss of the asset could result in unacceptable consequences for life safety, the economy, society or the network even if the regulations have been followed. If the answer to this question is yes, then the guarantee objectives must be maintained so as to reduce the damage, ensure the continued operation of the service, maintain emergency operability and allow for recovery. It is important to make this distinction since risk-based engineering must never be used to lower the mandatory level of protection.

The reason given for introducing the second layer in Vision 2030 is that further investment in advanced infrastructure and digital transformation results in a greater value and a higher level of complexity being attached to the nation's assets (Saudi Vision 2030, 2024). A durability framework helps to achieve these aims by making sure that systems remain available, by improving the reliability of design solutions, and by providing evidence for investment throughout the entire lifecycle of the asset. It also sets up a common vocabulary which can be used by designers, operators, regulators, insurers, and emergency services; this vocabulary consists of terms such as criticality, credible scenario, performance objective, barrier reliability, recovery target, and residual risk.

5. Proposed Risk-Based Engineering Framework

Figure 2 shows that the evidence involves five stages: anticipate; prevent and protect; absorb and respond; recover; and learn and adapt. In the first stage, the asset's mission, its critical functions,

its dependencies, its occupancy characteristics, the hazardous stocks it contains, the ignition sources and the possible fire scenarios are defined. When selecting the scenarios it is necessary to combine deterministic code cases with risk-informed degraded conditions, and to each scenario there must be associated specific performance objectives concerning life safety, structural stability, smoke tenability, responder access, the containment of hazardous escalation, the continuity of essential functions, and the maximum acceptable recovery time.

During the second stage the barrier structure is set up. The preventive measures include ignition control, hazardous-work management, housekeeping, electrical integrity and process isolation, whereas the protective measures are compartmentation, fire resistance, detection, alarm systems, suppression, smoke control, emergency power and a protected means of egress. For high-consequence assets, special attention must be paid to independent operation and the possibility of common-cause failure. Evidence from tunnel systems shows that the interactions may be non-linear; it is therefore essential that the verification plan considers combinations rather than suppose that the system's performance is equal to the sum of the individual ratings (Liu et al., 2021; Lombardi et al., 2023). Design reviews should record the assumptions, the acceptance criteria and the evidence that supports each of the key barriers.

The following phase comprises absorption and reaction. The asset has to be capable of staying within its safe operating limits after the initiating event, must deliver accurate information to both the occupants and to emergency responders, should allow for either an evacuation or a defend-in-place strategy depending on the situation, and must permit a controlled shutdown without causing any secondary hazards. Emergency command needs clear information about the position of the fire, the manner in which the smoke is spreading, which systems are not working properly, what hazardous materials are involved, and details concerning the occupancy and access routes. When digital twins or AI are used, the outputs should include a statement about the level of confidence and must be backed by conventional instrumentation and procedures (Khan et al., 2022; Xie et al., 2025). The exercises should include partial system failure and uncertain information in order to evaluate how people perform under realistic conditions.

In the fourth stage, recovery turns into an engineering issue. The owners must set recovery time and recovery point objectives for the main functions, determine the simplest possible service configurations, and decide which equipment, utilities, data, spares and external approvals are

needed in order to get the system going again. Resilience assessments should also consider indirect damage effects such as smoke contamination, suppression water, control-system failures, and areas that have become inaccessible, not just the part that has caught fire (Himoto et al., 2024). When a single component has the potential to cause a long-lasting disruption, it might be more effective to use redundancy, physical separation, alternative routing, or strategic spares than to add more reinforcing components that are already strong.

The cycle is closed through acquisition and adjustment. The experience obtained from near misses, nuisance alarms, suppression system activations, maintenance problems, the results of drills and actual incidents should be fed into a controlled assurance process. Examples of leading indicators are critical maintenance which is overdue, egress routes which are not available, detector faults, suppression zones which have been disabled, fire-stopping defects which have not been corrected, failed emergency communications, and the failure to close out drill actions. Lagging indicators comprise fire frequency, barrier failure, injury, the extent of the damage, and downtime. A quarterly durability review should combine these measures with change-management data in such a way that any introduction of new technologies, changes in occupancy, or modifications to processes lead to a reappraisal, rather than allowing the risk profile to change silently.

There are four assurance layers that apply to all five stages: governance sets ownership, guarantees competence, provides for independent review and retains the remaining risk; digital intelligence offers reliable sensing, allows for the combination of data and supports modelling; human reliability is in charge of training, guarantees accessibility, facilitates communication and exercises judgment; and continuity engineering takes care of the dependencies and the recovery resources. As a result, fire protection moves from being a set of individual installed systems to becoming a managed safety capability. The framework is compatible with the prescriptive Saudi codes since it starts with compliance; its additional value lies in the fact that it explicitly considers criticality, uncertainty, degraded states, interdependencies, and recovery.

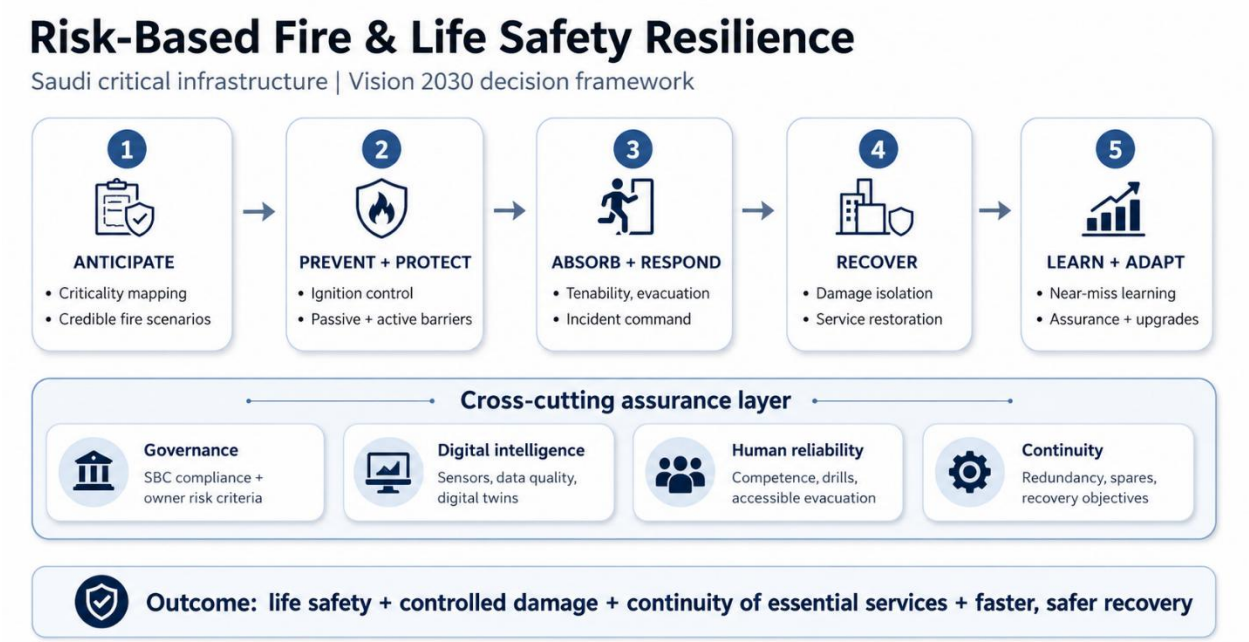

Figure. Risk-based fire and life safety resilience framework for Saudi critical infrastructure.

437 **Table 2. Engineering domains, verification indicators and controls in the proposed**
438 **resilience framework**.

Framework domain	Primary engineering question	Example indicators / verification	Priority controls
Anticipate	What can burn, fail or cascade, and which services are mission-critical?	Asset criticality; scenario register; hazardous inventory; dependency map; consequence categories.	Ignition control; process isolation; criticality-based scenario selection; change management.
Prevent + protect	Will independent barriers control fire and smoke under credible degraded conditions?	Detection availability; suppression reliability; compartmentation defects; smoke-control test results; structural fire criteria.	Passive protection; alarm/detection; suppression; smoke management; emergency power; protected egress.
Absorb + respond	Can occupants and responders act safely while the asset degrades?	ASET/RSET evidence where applicable; command readiness; radio coverage; drill findings; responder access.	Evacuation/defend-in-place strategy; fire command centre; incident procedures; information fusion; fallback modes.

Framework domain	Primary engineering question	Example indicators / verification	Priority controls
Recover	How quickly can essential service be restored after direct and secondary damage?	Recovery-time objective; minimum viable service; spares lead time; utility redundancy; restart criteria.	Damage isolation; alternate routing; protected spares; contamination/water-damage plans; phased restart.
Learn + adapt	Does operational evidence trigger timely correction and redesign?	Near misses; impairments; overdue safety-critical maintenance; recurring alarms; action closure; change reviews.	Assurance dashboard; audits; independent review; lessons learned; periodic revalidation.
Cross-cutting assurance	Are governance, human reliability, digital systems and continuity resources dependable?	Competence; ownership; data quality; cybersecurity; accessibility; supplier dependency; residual-risk acceptance.	Defined accountability; verified digital tools; training; multilingual communication; continuity planning; documented safety case.

6. Discussion and Practical Implications

From the synthesis three conclusions may be reached. The first is that the most important design change should be to define success not just in terms of evacuation, because with respect to critical infrastructure success consists in either maintaining the essential services running or in

restoring them quickly without compromising life safety. The second is that more attention should be paid to the way in which the various systems interact rather than to specifying the individual components, as experimental and computational studies have shown that ventilation, suppression, smoke movement, sensors and human decisions interact, and therefore resilience reviews should make use of scenario-based integrated testing and commissioning. The third is that data should be incorporated into fire-safety assurance; even if digital tools can enhance prediction and inspection, this is only possible if validation, cybersecurity, fallback operations and accountable human decisions are specifically considered.

The Saudi owners, in cooperation with the relevant authorities, have no reason to wait until new regulations have been introduced before taking action; rather, they should carry out a criticality screen so as to determine which assets need a more in-depth examination, after which the existing fire strategies can be expanded to include resilience objectives, scenarios that involve degraded conditions and recovery targets. At the design stage, the safety cases should explain why the selected scenarios and barriers are adequate. It is essential to use operational dashboards in order to monitor both the availability of the barriers and the implementation of any corrective actions. Periodic exercises should be carried out to check the responder interfaces and the continuity plans. Consequently, the alignment with Vision 2030 changes from being merely a general statement to becoming specific engineering practice and this in turn results in fewer uncontrolled escalations, better life safety, clearer assurance of the safety of the innovative assets and shorter interruptions to nationally important services.

A direct result of this is that resilience governance must distinguish between the kind of evidence needed when a design is approved and the kind that is needed during operation. At the design stage the evidence required could consist of fire modelling, an evacuation analysis, a structural fire assessment, cause-and-effect matrices for systems, and a demonstration of emergency access. As for operations, the evidence should indicate that the installed configuration remains in accordance with the approved strategy through the use of inspection, maintenance, impairment management and controlled change. This approach stops a well-designed system from slowly deteriorating in an unnoticed manner after it is handed over and enables asset owners to have a sound basis for prioritising their maintenance spending in accordance with the safety significance and service criticality of various items, rather than allocating resources equally among all

defects. For large projects, an independent technical review should concentrate on the assumptions which have the highest consequence sensitivity. Periodic revalidation should also be initiated because of factors such as increased occupancy, changes in materials, process intensification, upgrades to digital systems, or a trend of repeated alarms and impairments. In this way, risk-based engineering becomes both a governance discipline and an analytical method.

7. Limitations and Future Research

This is not a statistical meta-analysis but a synthesis of structured frameworks, the evidence for this being drawn from a variety of types of infrastructure and involving a wide range of study methods. As a result, the move to Saudi assets will have to be based on specific engineering judgments for each individual project. The type of research that should be given priority consists of setting up a national anonymised database on fires and near-misses, carrying out an investigation into Saudi recovery-time statistics, conducting full-scale tests of emerging energy and transport technologies, verifying digital-twin predictions under local operating conditions, and carrying out studies on evacuation and responder performance in complex multilingual facilities. Future research should also involve testing the proposed indicators in a number of different infrastructure sectors and look at how failures in interdependencies spread beyond the fire-damaged asset.

It must also be verified that clear ownership is defined for each critical barrier and recovery action.

The asset-level resilience targets should be reviewed every time there is a change in occupancy, fuel load, dependency, or emergency access.

Transparent documentation is essential since the decisions made on the basis of risk must be understandable to future operators and reviewers.

The framework in question is intentionally designed to be modular in order that the regulators for each sector may add criteria which are specific to the hazards without being required to alter the logic of the framework's lifecycle.

The verification carried out by Saudi Arabia should focus on evidence which links the physical effects of a fire with the actual times for service interruption and for restoration.

It may therefore be concluded that if research is to be carried out in Saudi Arabia in the future, it should employ clear and reproducible criteria for linking together incident learning, engineering validation, operational assurance, emergency preparedness, recovery evidence and cross-sector governance if it is to ensure that the investment made is proportional, that decisions can be held accountable and that continuous improvement occurs with regard to the country's important infrastructure throughout the asset's entire lifecycle in practice.

8. Conclusion

Fire and life safety resilience with regard to Saudi critical infrastructure must be treated as a lifecycle engineering aim that is based on and goes beyond compliance with the relevant codes. The available evidence shows that such a framework involves first assessing the importance of the assets and the possible scenarios, incorporating both technical and organizational safeguards, checking for degraded conditions, aiding emergency command in making decisions, planning recovery before an incident occurs, and using operational data as a way of achieving continuous learning. The application of this risk-based approach in conjunction with the 2024 Saudi codes will help to protect people, reduce cascading disruption and ensure that the infrastructure necessary for Vision 2030 remains operational.

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