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Integrated Fire Alarm, Emergency Power and Smoke-Control Systems for Enhancing Building Resilience in Saudi Arabia

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Abstract- ***How tough a building can be made out to be in the event of a fire depends on whether the life-safety systems function as a single, coordinated protective chain or whether they remain as separate systems that merely meet code requirements. This study examines the integration of fire alarm, emergency power and smoke control systems in buildings in Saudi Arabia, with a special emphasis on high-rise buildings, mixed-use developments, healthcare facilities, hotels and other large public buildings in the light of the country's rapid urban development. A structured integrative review was carried out using thirty sources published between 2020 and 2025, combining peer-reviewed research on fire safety, evacuation procedures, sensing technology, power reliability and digital twins with the existing Saudi and international standards. The evidence was organised according to the areas of detection and notification, power continuity, smoke tenability, interface logic, commissioning and operational governance. The synthesis indicates that resilience is most at risk at the points where the systems interact: at the interfaces between the alarm system and the control system, when switching to standby power, when receiving feedback from dampers and fans, along the communication links, and when operators have to interpret conflicting status signals. Emergency power should therefore be regarded as a layer which guarantees the continuity of life-safety, while smoke control should be checked to make sure that it operates as a dynamic tenability feature that is initiated and monitored via reliable alarm logic. The paper suggests an endurance assurance framework for Saudi Arabia based on dependency mapping, cause-and-effect verification, integrated testing, fault visibility and the availability of evidence throughout the whole lifecycle. The review concludes that improved co-ordination between designers, specialist contractors, commissioning teams, facility managers and the relevant authorities can turn prescriptive compliance into real, measurable continuity during a fire and into faster recovery.***

I. INTRODUCTION

At the moment, Saudi Arabia is increasing the number of high-rise towers, hospitals, hotels, transport facilities, entertainment venues and mixed-use developments; this trend is placing an extremely heavy demand on fire and life-safety engineering. These buildings are not simply larger versions of normal structures since they have dense electrical and mechanical systems, include a variety of requirements regarding the occupants, provide extensive vertical circulation, involve complicated compartmentation and are fitted with ever more complex digital control systems. As a result, they are depending increasingly on coordinated emergency procedures. A detector may correctly detect a fire, but the occupants could still be exposed to unacceptable conditions if the alarm logic fails to start the appropriate smoke-control sequence, if a fan loses power when switching over to a generator, or if the status feedback does not indicate that a damper has failed. Building resilience therefore relies on the continuous operation of an integrated system which includes sensing, decision-making, power and environmental control.

The fire safety reports show a change in focus from emphasizing the reliability of individual components to giving greater importance to the durability of the entire system. McNamee and Meacham (2025) define fire resilience as the ability of the built environment to cope with, adapt to and recover from disruptive fire events, rather than just seeking to meet a minimum level of protective standards. Frantzich et al. (2025) reach the same conclusion by advocating decision-making models that assess sustainability and fire resilience side by side and by recommending that designers consider existing dependencies, performance trade-offs, and long-term consequences. This view is particularly relevant to Saudi Arabia since

the Vision 2030 development programme places a strong emphasis on service continuity, quality of life, digital transformation and durable infrastructure (Saudi Vision 2030, 2025).

Three of the buildings have technical systems which are highly interdependent. The fire alarm system is capable of detecting abnormal conditions, of giving warnings and of carrying out the pre-determined control actions. The emergency and standby power systems ensure that essential electrical functions continue to operate whenever the normal power supply is not available or has been deliberately switched off. The smoke-control systems employ fans, dampers, pressure differences and control logic in order to prevent the spread of smoke and to make sure that escape routes or the paths for firefighting operations remain usable. Requirements relating to fire alarm and detection, smoke control and emergency or standby power are included in the Saudi Building Code within the context of fire safety (Saudi Building Code National Committee, 2024a, 2024b). Internationally, NFPA 72, NFPA 92 and NFPA 110 provide well-established technical principles concerning signalling, smoke-control design and emergency-power performance (NFPA, 2022, 2024, 2025).

The problem is that when compliance documents are examined, each subsystem is evaluated using separate specialist software packages, even though the way the systems perform during a fire event is something that all of them share. This lack of integration may hide common-cause failures and lead to uncertainty regarding responsibility at the interfaces. That is the reason why the present review treats integration as a factor affecting resilience and looks into how the fire alarm, emergency power and smoke control systems should interact, what faults could occur in their dependencies, and how Saudi projects can make sure that the overall performance is checked at every stage of the design, commissioning and operation.

II. AIM AND OBJECTIVES

This review is intended to establish an integration model, with a focus on resilience, for the fire alarm, emergency power and smoke-control systems in buildings in Saudi Arabia, the objective being to make sure that the life-safety functions continue to operate during times of degradation or in emergency situations and not merely to check that each individual piece of equipment complies.

The study has four objectives. The first of these is to gather information about the technical dependencies and the distribution of failures in the fire detection, alarm control, standby power and smoke management systems over the period in question. The second objective consists of interpreting the requirements specified in the Saudi and international codes from the point of view of resilience features such as availability, redundancy, fault tolerance, tenability and recoverability. The third objective is to identify commissioning and operational indicators which will reveal latent interface or common-cause failures before an emergency takes place. The fourth objective is to propose a lifecycle assurance framework that is suitable for use in complex projects in Saudi Arabia and can be adapted for use in digital management.

The review regards resilience not as a form of redundancy but as a way of evaluating performance; specifically, it is the capacity to keep essential fire-safety outcomes intact even if the equipment, utilities, communications, or the operating assumptions are degraded. Using this method it is possible to compare different technologies without implying that one design method is in general superior to another. Moreover, it guarantees that the objectives in question can be used both for new buildings and for existing ones which are being retrofitted, have their systems replaced, or are going through digital modernisation.

III. REVIEW METHODOLOGY

A structured integrative review method was chosen since the research question covers a wide variety of different kinds of evidence which cannot easily be combined using statistical meta-analysis. The performance of fire alarms is assessed in terms of detection, signalling, and reliability; emergency power is looked at in the literature on electrical reliability and in the material dealing with standby energy; smoke control is examined through experiments, computational studies, and reviews of ventilation systems; and resilience together with governance is illustrated by standards, systems-thinking publications, and the Saudi code sources. Although it makes use of a different coding structure that is oriented towards life-safety dependency and fire-event

continuity, this approach offers the same level of transparency as the narrative method used in the building-systems reference model.

The reference papers were taken as a starting point and the evidence set was developed by working backwards through the citations given in them, by consulting the publisher's records for any relevant peer-reviewed studies and by referring to official standards and government publications. In order to be included in the set, the sources had to have been published between 2020 and 2025 and had to have dealt with at least one of the five topics—fire detection and alarm; emergency or standby power for important loads; smoke movement or mechanical smoke control; evacuation and tenability; or integrated fire-safety resilience in buildings. Systematic reviews, experimental and simulation studies, reliability analyses, and papers that were directly concerned with multi-storey or complex buildings were given priority. The Saudi code, anything related to Vision 2030, and recent research into construction in Saudi Arabia were all incorporated in order that the synthesis might be more suitable to the local circumstances. Studies which focused exclusively on wildland fire behaviour, combustion chemistry, or on unrelated industrial process hazards were excluded unless they included evidence that could be applied to detection systems.

Thirty sources were kept and the sources were coded in two stages. During the first stage the evidence was assigned to the various functional layers, that is, to those relating to sensing and alarm, control interfaces, emergency power, smoke management, occupant response, and lifecycle governance. In the second stage the evidence was coded with respect to the resilience properties, namely dependency, redundancy, fault visibility, identification, recovery, and verification. Evidence-based comparisons were then carried out in order to detect recurring interface risks and to distinguish between a component failure and a system-level loss of function. Since the studies included heterogeneous outcomes, building types, and methods, a pooled effect estimate was not computed; rather framework synthesis was used to link the engineering evidence with the code-driven responsibilities.

The quality of the review was improved through the process of translation; it was considered to be more solid when a technical finding was backed by more than one type of evidence, for example, by combining a review of smoke control with an experimental study of high-rise buildings, or by pairing a reliability model with a prescriptive standard. The review does not include carrying out a full PRISMA systematic search of all the bibliographic databases; rather, its aim is to provide an applied, transparent, and limited synthesis that is suitable for the purpose of developing a Saudi-oriented integration framework. This method prevents overestimating the degree to which the literature has been covered while at the same time ensuring that the selected evidence is traceable.

IV. SAUDI CONTEXT AND RESILIENCE REQUIREMENTS

The fire-safety design in Saudi Arabia must take into account the fact that the construction industry is changing rapidly and therefore involves cooperation between imported technologies, international consultants, local authorities, and specialist subcontractors for each building. As Jamoussi et al. (2022) point out, the country's building standards and certification procedures are continuously being developed, and Alaboud and Alshahrani (2023) note that digital construction methods have become a major feature of the nation's projects. Although these developments provide the opportunity to incorporate life-safety information at an earlier stage, they also lead to a greater number of interfaces that have to be coordinated.

The National Committee of the Saudi Building Code (2024a, 2024b) says that SBC 801 contains the regulations concerning fire alarm systems and detection as well as smoke control, whereas the general building code provides the framework for emergency and standby services. Although NFPA 72 (2022), NFPA 92 (2024) and NFPA 110 (2025) clearly lay down the requirements for signalling integrity, smoke-control engineering and emergency power systems, they are still useful as supplementary references. However, with regard to resilience, the important issue is not whether the project has listed the correct standards; it is whether the completed installation will be able to keep the intended sequence

when the normal power becomes unstable, communications fail, a device malfunctions or a fire alters the physical environment.

The example from Saudi Arabia demonstrates that this issue must be considered in practice. Large buildings typically have a high demand for cooling, usually include a large number of vertical shafts, involve long cable and communication runs, place a heavy demand on the smoke-control fans and have complicated phased handovers. Since dust, heat and the high level of occupancy are present, more maintenance is required. Conversely, in the case of prestige properties it is essential that their operations should not be interrupted and that services should be able to be restarted quickly after a disruption; that is the reason why a resilience-based approach goes beyond fulfilling prescriptive standards by requiring proof that the life-safety functions remain visible, powered and co-ordinated under credible degraded conditions.

V. FIRE ALARM AS THE TRIGGERING INTELLIGENCE LAYER

The fire alarm system is the intelligent component of the integrated protection system. In the traditional approach it has carried out the functions of detection, gave an alert, performed supervision and communicated any abnormal conditions, but in modern buildings the fire alarm control system is also used to initiate or coordinate actions outside the alarm network. These actions may include opening doors, recalling lifts, ordering smoke dampers, switching on extraction or pressurisation fans, switching off certain air-handling equipment and communicating the system's status to a fire command centre. As specified in NFPA 72 (2022) there is a strong emphasis on signalling paths, supervision and system soundness, while the Saudi code lays down the local compliance standards. Regarding resilience, the value of the alarm system is based on the reliability of both its decisions and of its interfaces.

Research carried out recently on sensing makes it clear that detection quality is not able to be separated from response quality. Khan et al. (2022) examine the advances achieved in fire sensors and note the general move towards multi-parameter and intelligent detection. Wen et al. (2021) demonstrate how the fusion of data from multiple sensors can be used when making decisions to sound an alarm, thereby decreasing the dependence on one single physical indicator. Jin et al. (2023) look at deep-learning methods applied to video fire detection, and Saponara et al. (2021) show that real-time recognition of fire and smoke using a camera is possible. Vorwerk et al. (2024) then show that multi-sensor classification can allow for earlier and more discriminating identification of fire. Even though these technologies may improve situational awareness, they also result in a greater dependence on the quality of the data, the communication systems, and the algorithmic interpretation. Intelligent detection should therefore be meant to enhance, not concealing, verifiable cause-and-effect relationships.

Reliability studies show that the architecture of an alarm system can itself be a major weakness. Jakubowski et al. (2021) look at focused, dispersed and combined fire alarm systems in buildings that are part of critical infrastructure and demonstrate how the topology of the system influences the system's operational reliability. Klimczak et al. (2022) specifically connect the reliability of fire alarm systems with the method of power supply and prove that the way power is arranged has an effect on system availability. The importance of these conclusions is that in complex projects in Saudi Arabia a seemingly redundant alarm network may still share power supplies, communication paths, interface modules or exposure to the environment, thereby creating common-mode risks.

The key resilience measure is therefore not simply the number of detectors or the inclusion of panel redundancy; it is the verified end-to-end operation. An credible integrated test has to begin with a representative initiating event and then verify notification, the transmission of commands, the power status, the movement of the fans or dampers, the feedback, the prioritisation of alarms, and the display for the operator. It should also include negative and degraded scenarios such as the loss of normal power, one failed interface, a disabled communication segment, or contradictory field feedback. These tests show whether the control matrix stays understandable during stress. Table 1 provides a summary of the representative dependencies and verification

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indicators for the three main systems and their interfaces.

Table 1. Integrated life-safety dependencies, vulnerabilities and resilience-oriented verification indicators.

System / interface	Primary resilience dependency	Typical latent or common-cause vulnerability	Indicative verification KPI
Fire detection and alarm	Reliable sensing, supervised signaling path, stable control logic and primary/secondary power.	Shared power supply or network path; disabled point; nuisance-prone sensing; incorrect zone or cause-and-effect programming.	Initiation-to-command time; alarm-path availability; percentage of supervisory faults resolved within target time.
Alarm-to-control interface	Verified cause-and-effect matrix, interface modules, command priority and actual-status feedback.	Command issued without field action; mislabeled point; one interface serving multiple critical functions; stale control database.	Percentage of commands with verified feedback; command/status mismatch rate; integrated scenario pass rate.
Emergency/standby power	Generator or alternate source, ATS, batteries/UPS, protected distribution and correctly classified critical loads.	Generator starts but transfer fails; control power omitted; breaker coordination issue; shared ATS; excessive simultaneous motor inrush.	Transfer success rate; transfer time; voltage recovery; percentage of required life-safety loads energized.
Smoke control / pressurization	Correct fan and damper sequence, power continuity, leakage assumptions, pressure sensing and manual override.	Stuck damper; VFD trip; incorrect fan rotation; open doors; failed pressure sensor; command active without stable pressure field.	Fan-start success; pressure stabilization time; differential-pressure compliance; unresolved device faults.
Fire command / operator layer	Prioritized annunciation, consistent asset naming, clear power and smoke-control status, protected communications.	Alarm flooding; ambiguous graphics; conflicting statuses; workstation/network failure masking field condition.	Critical-point display completeness; fault visibility time; operator acknowledgement and corrective-action time.

VI. EMERGENCY POWER AS THE CONTINUITY LAYER

The emergency power system is essential in order that the fire strategy may go on in the event of an electrical disruption. A fire might have a direct effect on circuits, cause the protective isolation to be activated, or happen at the same time as a failure of the utility supply. When the life-safety plan relies on electrically powered smoke-control fans, pressurisation systems, alarm panels, communication equipment, or certain lifts, the emergency power supply, the transfer system, and the downstream distribution become an important part of fire-safety considerations and are not simply included within the electrical service. As noted in NFPA 110 (2025), the performance requirements for emergency and standby power systems are specified, the areas covered including source readiness and the way in which the transfer process operates. The building regulations of Saudi Arabia take the same view by considering emergency and standby electrical arrangements as forming part of safe building operation (Saudi Building Code National Committee, 2024a, 2024b).

In 2022, Zhang and his colleagues looked at the reliability and cost of integrated emergency power systems in building complexes and found that it is necessary to evaluate various power sources and different system designs as part of the whole system rather than treating them as separate generators. In 2024, Wiśnios and his co-authors expanded the reliability analysis to cover the power arrangements for electronic security systems in smart buildings, stressing the importance of the different states of supply and the way in which failures occur. The researchers gave an example based on a fire alarm that is directly applicable: the probability of the alarm continuing to function depends on the configuration and on the reliability of its power supply. Taken together, these studies show that resilience can be improved by explicitly linking critical loads to the durations they require, to their transfer sequence, to the diversity of their power sources, and to the consequences of failure.

The usual weakness is generally located somewhere between the generator and the life-safety equipment. For instance, a standby generator will be able to start properly even if the automatic transfer switch fails, if the downstream circuit breaker trips, if the control transformer is not connected to the emergency bus, or if the communication gateway restarts while the transfer is taking place. The smoke-control motors use a large amount of starting current and when several of them are operated in sequence this may affect the electrical stability or the generator's capacity. Although battery-powered alarm circuits are sufficient for short transfer periods, they are not capable of making up for a misclassified feeder or for a loss of control power at a motor starter. The emergency-power design must therefore be studied in relation to the real cause-and-effect sequence, not just the connected-load schedule.

The cold-start behaviour, transfer time, sequential starting, voltage recovery, control-system reboot, alarm persistence, and the system's capacity to return to normal supply should all be looked at in the resilience-based test programme. It is also necessary to make sure that the overrides stay operational when the supervisory networks are not available. The goal is to achieve graceful degradation: if a noncritical digital component fails, the essential life-safety function should still be maintained by means of the local logic that is aligned with it. This principle is in agreement with the wider literature on resilient control, which considers it to involve state awareness, independent functions and explicit resource restrictions (Almatared et al., 2024; Lin et al., 2025).

VII. SMOKE CONTROL AS THE TENABILITY LAYER

Smoke control is important for ensuring tenability within the integrated system since the majority of evacuation problems are related to smoke, visibility loss and the way in which smoke moves being major factors in allowing people to leave safely. Alianto et al. (2022) examined mechanical ventilation and stairwell pressurization in high-rise buildings and stressed the importance of coordinating pressure control, leakage paths, and ventilation operation. When Kallianiotis et al. looked at underground spaces, they found that the effectiveness of smoke control depends on the interaction between the conditions, the ventilation settings, and the spatial configuration. He et al. (2020), by using a full-scale high-rise stairwell, showed that the location of the opening has a significant effect on smoke transport. These results show a fundamental principle pertaining to resilience: smoke control cannot be evaluated simply by checking whether the fans are operating.

Most smoke-control sequences involve a series of interdependent actions. The alarm system determines the location of the fire; the programmed logic then causes the appropriate dampers and fans to operate; emergency power makes it possible for the equipment to keep working if the normal power supply is interrupted; feedback is acquired by means of pressure sensors and end switches; and the operators are provided with status information so that they can take action. A fault at any point can impact the pressure field, since doors opened by occupants or firefighters can change the leakage levels and a defective damper can produce an unintended flow path. Choi et al. (2025) stress the importance of smoke-control strategies which allow evacuation when fire conditions are changing rather than considering ventilation as a fixed design condition.

Research into evacuation procedures also indicates that tenability should be regarded as a dynamic factor.

Wang et al. (2024) carried out an optimized evacuation in a high-rise building and demonstrated that the condition of each floor is related to time. In their agent-based evacuation simulation, Senanayake et al. (2024) stressed the importance of crowd behaviour, congestion, and realistic movement. Lyu et al. (2025), who focused on people with functional disabilities, found that the standard assumptions regarding occupant mobility may not consider vulnerable groups. It therefore follows that smoke-control resilience must be assessed in terms of its capacity to maintain usable egress conditions for a variety of occupants, and not simply on the basis of attaining a design pressure at a single test point.

Digital methods have the capacity to improve verification and situational awareness. Lotfi and others (2021) apply a method based on BIM in order to evaluate evacuation after a fire has occurred as a result of an earthquake, showing the way in which spatial data can link hazard assessment with egress evaluation. Almatared and his co-workers (2024) suggest a digital-twin framework for fire-safety management that integrates building information with operational data. Lin and others (2025) look at digital twins of both buildings and occupants in the context of emergency evacuation, while Yen and Lin (2024) provide an example of evacuation signs that are dynamically controlled by means of IoT technology. Concerning projects in Saudi Arabia, these technologies are most useful for revealing the physical condition of the smoke-control system—specifically the difference between the commanded and actual damper position, the fan status, the pressure trends, the alarm zone, the power source and the fault condition. Digital visualisation should be designed so that the dependencies become clear rather than introducing another layer which might fail without being noticed.

VIII. INTEGRATED RESILIENCE ARCHITECTURE AND PERFORMANCE

The available evidence indicates that resilience appears at the points where the alarm systems, the power supply and the smoke control systems interact. Even though the specifications for each individual component outline the separate duties of each subsystem, an emergency sequence relies on a series of ordered interactions. As illustrated in Figure 1, the proposed integrated life-safety resilience architecture includes detection and sensing feeding information to the alarm decision layer; the verified cause-and-effect matrix sending out commands; emergency power making sure that the necessary electrical routes remain active; the smoke-control equipment altering the building environment; and feedback transmitting the physical status back to the fire command function. The loop is not considered to be closed until the operator is able to tell the difference between a successful command and a failed action.

Resilience can be understood by looking at four of its properties. The first of these is anticipation; prior to the system being built, the designers identify the dependencies, the common-cause vulnerabilities, and the possible degraded states. The second characteristic is the use of protected circuits, standby power supplies, and fail-safe positions for the emergency and local controls, so that a single fault does not result in the complete failure of the life-safety function. The third is adaptation; rather than staying fixed on the nominal scenario, both the system and the operators react to changes in the conditions concerning smoke, occupancy, and the state of the equipment. The fourth is recovery; restoration and the opportunity to learn following an incident are enabled by logs, evidence from tests, and data on maintainable assets. As McNamee and Meacham (2025) and Frantzich et al. (2025) point out, there is a more general resilience reason to regard these capabilities as part of the performance of the built environment.

Special attention should be paid to common-cause failures since conventional redundancy can be misleading. For example, if two fans make use of the same transfer switch, then they are not independent of each other. In the same way, two communication loops might share a single network cabinet, riser, or power supply. Even when several dampers each have their own actuator, they can still receive their commands via a single interface module. Also, both the primary and the backup graphical workstations could show the same incorrect database point. These examples show that merely adding redundant components is not enough; dependency mapping should be used to identify the dependencies relating to energy, commands, communication, and the physical

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environment that extend from the device causing the failure to the final life-safety outcome.

The method also has an effect on how performance is measured. Instead of simply noting whether or not each device passes or fails in traditional acceptance testing, a durable test should consider sequence time, transfer continuity, status-confirmation latency, the number of critical loads that are unavailable, the success of fan starts, pressure stabilization, the visibility of failed commands, and recovery time. These indicators are not meant to replace the acceptance criteria specified in the code; rather, they make the system's behaviour measurable through different interfaces. With regard to valuable assets in Saudi Arabia, taking recordings of these items during commissioning establishes a baseline that can be used in subsequent periodic testing and in digital facility management.

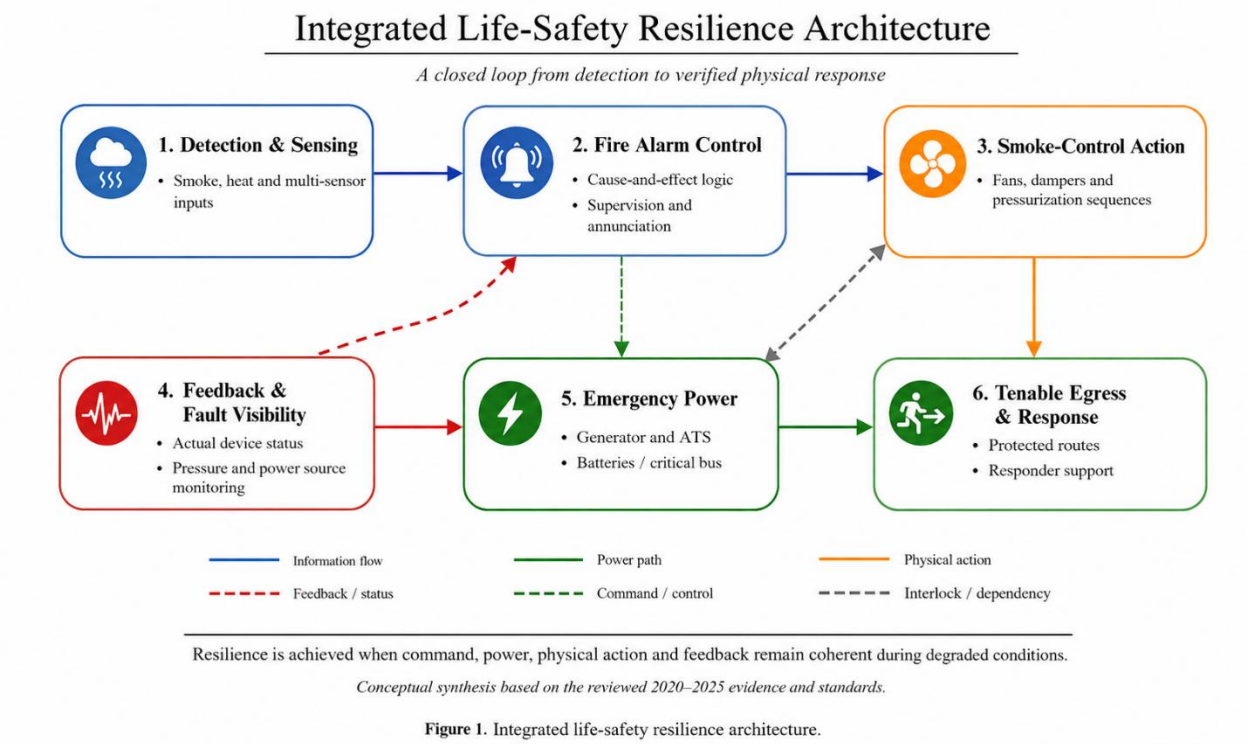

Figure 1. Integrated life-safety resilience architecture.

IX. DISCUSSION: COMMON-CAUSE FAILURE, COMMISSIONING AND GOVERNANCE

The key point of this review is that technical integration must be combined with organisational integration. Fire alarm contractors, electrical contractors, mechanical smoke-control specialists, BMS integrators, commissioning teams and facility operators generally operate under separate contracts. Each of them draws up its own checklist even though no one is overall responsible for the entire emergency sequence. As a result, the equipment may be technically in compliance yet will be linked together via poorly managed interfaces. It is thus essential for an endurance specification to clearly allocate responsibility for the cause-and-effect matrix, the interface register, the emergency-load schedule, the integrated testing script and the final evidence set.

The stage at which assumptions become observable behaviour is called commissioning. A dependable programme should progress from testing individual devices to testing subsystems and then to integrated scenarios, as well as to tests that include degraded modes. For instance, one scenario might cause a detector in a standard zone to activate while normal power is still available; a second scenario should carry out the same sequence after the normal power supply has been lost; a third scenario could involve a failed

damper or a communication fault. The test has to confirm not only that the smoke-control equipment responds but also that the failure is clearly shown and that the operators are able to carry out an alternative action. This approach is in agreement with reliability studies which emphasise the operational implications of the system's configuration and power architecture rather than the nominal availability of the equipment (Jakubowski et al., 2021; Klimczak et al., 2022; Wiśnios et al., 2024).

Human factors remain important since, even though advanced alarm analytics, digital twins, and dynamic signage can offer more detailed information, emergency personnel have to work within time limits. If a control centre shows hundreds of alarms without prioritising them, has inconsistent naming, or uses graphics that do not correspond to the real building, then adding more data might actually have a negative rather than a positive effect upon resilience. The purpose of integration therefore is to enhance the quality of decision-making and the information given should be capable of answering five key questions at once: where the suspected fire is, what life-safety sequence has been activated, which actions have been successful, which critical loads are being supplied by emergency power, and what conditions are threatening egress or firefighting routes. Research into digital twins and IoT is of assistance to the extent that it supports this basic situational model (Almatared et al., 2024; Lin et al., 2025; Yen and Lin, 2024).

Maintenance poses a second integration challenge because fire alarm equipment can be inspected as part of one maintenance routine, generators as part of another, and smoke-control components as part of a third. When maintenance records are kept separately, it becomes hard to tell whether the full sequence remains valid after software changes, alterations made by tenants, the replacement of dampers or electrical modifications. Resilience programme must ensure that re-verification takes place every time a change affects interfaces or essential dependencies. In projects in Saudi Arabia, BIM and digital records can assist with this process as national construction practice is gradually moving toward digital information workflows (Alaboud and Alshahrani, 2023). However, digital records are of no use unless the asset identifiers, the cause-and-effect logic and the field conditions are kept in step.

The case for introducing a lifecycle governance model also applies in Saudi Arabia, since large projects typically go through stages of construction, a partial opening and involve a number of operational teams. The organization responsible for the initial commissioning does not have to be the one that carries out the operation of the asset many years later. Table 2 therefore converts the review's findings into specific requirements relating to design, integrated commissioning, operation, periodic testing and post-event recovery. Such continuity is essential if a single approval is to lead to durable resilience.

Table 2. Saudi Resilience Assurance Framework: lifecycle actions and evidence requirements.

Lifecycle stage	Required integration action	Verification evidence	Saudi-specific emphasis	Owner-level resilience KPI
Design	Create one dependency map linking fire scenarios, alarm logic, emergency loads, smoke zones, feedback points and responsible parties.	Approved fire strategy; interface register; cause-and-effect matrix; emergency-load schedule; smoke-control calculations.	High-rise shafts, complex mixed uses, climatic loads, phased packages and authority interfaces.	100% of required life-safety functions traced end to end before procurement.
Integrated commissioning	Test representative fire scenarios and repeat selected scenarios under loss of normal	Signed integrated test scripts; trend logs; power-transfer records;	Phased handover and multiple specialist contractors must	Scenario pass rate; critical defects open at handover; command-to-

	power and injected faults.	fan/damper feedback; defect register.	not fragment acceptance evidence.	action and transfer times.
Operations	Maintain impairment control, synchronized asset identifiers, periodic testing and clear operator displays.	Inspection/testing records; impairment permits; alarm and fault history; updated schematics and graphics.	Heat/dust exposure, intensive occupancy and long operating hours can accelerate maintenance demand.	Critical-system availability; overdue impairments; repeat fault frequency.
Change management	Trigger impact review and targeted re-testing after software, tenant, electrical, HVAC or smoke-zone changes.	Management-of-change record; revised matrix; re-test evidence; updated digital/BIM asset data.	Fast fit-out cycles and staged openings can alter interfaces after initial approval.	Percentage of safety-significant changes closed with verified re-test.
Event and recovery	Capture event chronology, isolate failed dependencies, restore protection and convert lessons into revised test priorities.	Event log; root-cause analysis; restoration certificate; corrective-action closure and lessons-learned record.	Continuity expectations for high-value public, hospitality, healthcare and transport assets.	Time to safe restoration; recurrence rate; corrective actions closed within target period.

X. PROPOSED SAUDI RESILIENCE ASSURANCE FRAMEWORK

The Saudi Resilience Assurance Framework consists of five interconnected steps, as shown in Figure 2. The first step, mapping, determines the fire strategy, identifies the critical functions and maps out the dependency paths. Each necessary life-safety action is connected to its initiating condition, control interface, power source, field device, feedback signal and the responsible party. The second step, challenging, involves introducing credible degraded states such as the loss of normal power, the failure of one interface, the unavailability of network supervision or a stuck damper. The third step, verification, tests the integrated sequence and records the response indicators specified in Table 1. The fourth step, operation, transfers the verified logic, setpoints, test records and asset identifiers into the facility management system. The fifth step, learning, makes use of alarms, failures, drill results, maintenance findings and any actual incident to update the dependency model and to set the priorities for future tests.

The framework is intentionally neutral with regard to technology and therefore applies to both conventional hardwired systems, networked fire alarm systems and buildings that have been digitally enhanced. Its key characteristic is the need for evidence at the boundaries of the system. A project cannot be regarded as resilient just because the alarm panel, the generator and the smoke fans each pass their individual tests; it has to show that the required function continues to work through the transition from detection to decision, from normal to emergency power and from command to the actual physical smoke control response. This approach is compatible with compliance with the Saudi code and at the same time provides an additional measurable level of assurance for complex assets.

To carry out the implementation, the owner must keep a single controlled resilience file which includes the up-to-date cause-and-effect matrix, the dependency register, the emergency-load list, the smoke-control schematic, the integrated test results, the unresolved impairments and the approved changes. The file should be examined following any major modifications and before any change in occupancy

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that affects the evacuation or smoke-control assumptions. Having a succinct controlled record lessens the need for reliance on the knowledge of individual specialists and provides future operators with a traceable basis for deciding whether or not a modification needs partial or complete re-testing.

In the end, the framework tells the difference between resilience evidence and maintenance records in that the evidence has to show that the various systems are still able to produce the required combined result following faults, changes and power transitions, not just that each individual device had been inspected, serviced or reported as being available.

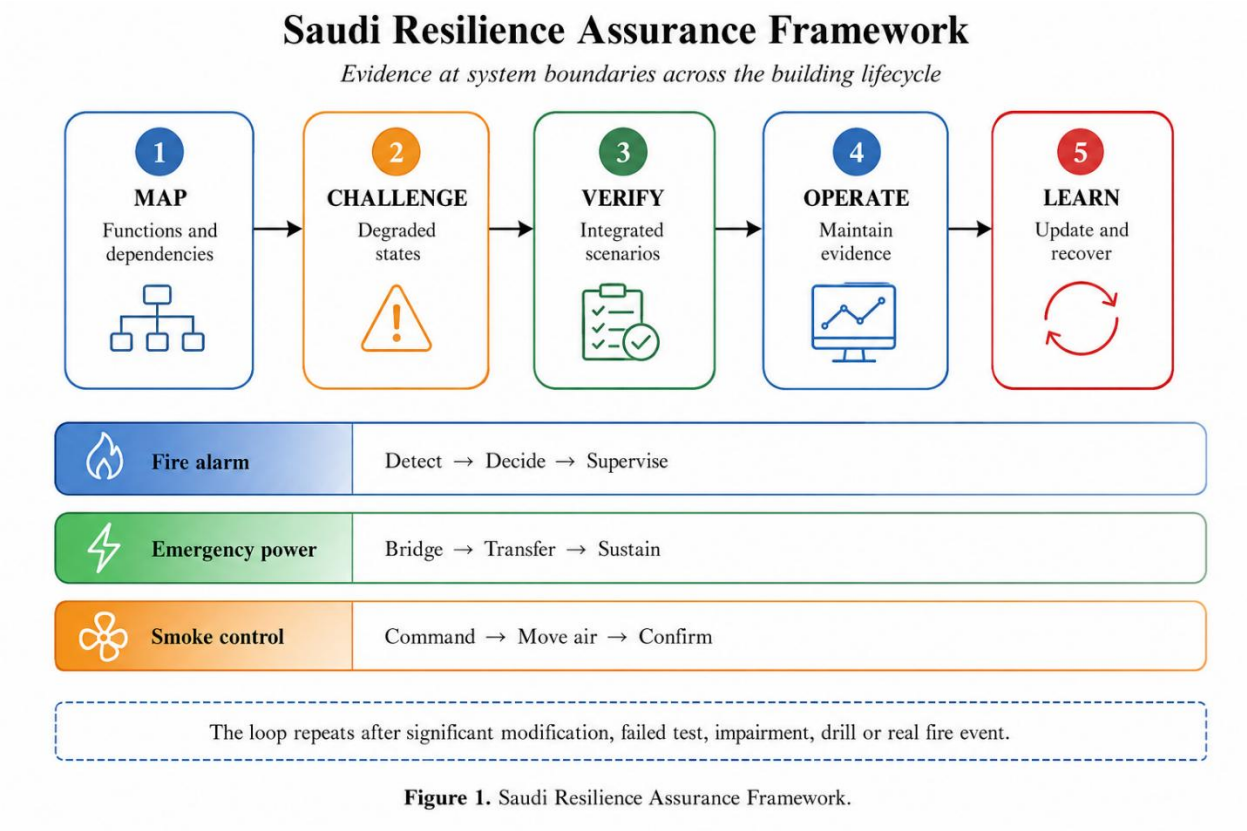

Figure 1. Saudi Resilience Assurance Framework.

XI. LIMITATIONS AND RESEARCH AGENDA

This review has three limitations. The first of these is that it is an integrative review and not a meta-analysis carried out with an exhaustive search of the database, the sample of thirty sources having been intentionally limited to more recent and directly relevant evidence. The second limitation is that the quantitative results from the studies concerning smoke control, evacuation and reliability cannot be directly compared because the building layouts, the fire scenarios and the performance criteria differ. The third point is that the amount of information currently available in the public literature on the results of integrated testing in Saudi operational buildings is still limited. It therefore follows that future research should include the gathering of anonymised commissioning and fault data from high-rise, healthcare, hospitality and transport projects in Saudi Arabia. Possible areas for further research should be probabilistic dependency models for common-cause failure, full-scale tests which combine emergency transfer with the startup of smoke control, a human-factors assessment of fire command interfaces, and digital-twin methods that verify rather than merely visualise the life-safety status.

A further priority is to collect benchmark data in Saudi Arabia on transfer times, the reliability of fan startups, pressure stabilisation, false-alarm behaviour and interface fault rates. On the basis of this data, later studies could move from qualitative dependency maps to probabilistic resilience targets. Moreover,

comparative research carried out in different climatic areas and for a variety of types of buildings could determine which failure modes are most influenced by heat, dust, patterns of occupancy, the quality of maintenance and the phased delivery of the project.

XII. CONCLUSION

How great fire resilience can be in Saudi Arabia depends on keeping a chain of life-safety functions going when the conditions are more severe than those met during normal operation. The fire alarm systems carry out the work of detection and supply command intelligence, emergency power ensures continuity, and the smoke-control systems maintain a tenable environment. The review shows that the weak points are generally to be found at the interfaces between these systems rather than in the main components of the systems themselves. Common power supplies, shared communication routes, unverified cause-and-effect relationships, incomplete feedback and fragmented maintenance can all undermine the apparent redundancy.

A strategy that focuses on resilience should therefore move beyond simply requiring compliance by including dependency mapping, testing in degraded modes, the use of measurable integrated performance indicators, and lifecycle governance. The framework proposed links design intent with integrated commissioning, operations and lessons learned after events have occurred. If it is applied to high-rise and other complex developments in Saudi Arabia, the approach will improve fault visibility, operational readiness and the ability to recover, while also aiding in the achievement of the wider Vision 2030 objective of having reliable, digitally managed infrastructure. The practical method of testing integration is simple in that when there is a fire and normal conditions cease, the building must still be able to detect the situation, make a decision, energise and control the smoke, alert the occupants and the responders, and clearly indicate at all times when any required action has not taken place.

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