Digital Twin-Based Performance Testing and Optimization of Advanced Fire Suppression Equipment for Saudi Industrial EPC Projects.

Abstract:

Industrial engineering, procurement and construction (EPC) projects require fire suppression equipment to perform reliably in the face of changing inventories, process hazards, hydraulic conditions and construction stage modifications. Traditional acceptance tests establish compliance at a number of selected operating points and say nothing about the potential for performance degradation between inspections or under the combined effect of multiple disturbances. This is a critical integrative review of the potential of digital twins to improve performance testing and optimisation of water based, gaseous and hybrid fire suppression assets in the Saudi industrial environment. A total of 30 DOI-traceable publications from 2020 to 2025 were reviewed in the areas of fire physics, cyber-physical modelling, operational validation and construction information management. The synthesis makes a clear distinction between geometric asset representations and true, synchronised, uncertainty aware digital twins and proposes a lifecycle framework which links engineering data, measured equipment states, validated fire scenarios and maintenance decisions. Evidence from suppression experiments shows that extinguishment is highly sensitive to droplet transport, obstruction, nozzle characteristics and boundary conditions. Digital twin studies show promise in terms of information integration but to date have seen very limited validation in the area of actual suppression. The review presents an equipment centred evaluation matrix, a staged credibility protocol and a constrained optimisation logic which is appropriate to the EPC handover context. Claims of extinguishment effectiveness must be backed by physical evidence rather than by simulated success. The key contribution of the review is the development of a practical research agenda for independently validated, auditable suppression digital twins operating under the climatic, operational and governance conditions that are relevant to the Saudi industrial project.

1 Introduction

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Fire protection in an industrial plant isn't just a bunch of pumps, nozzles and cylinders. It's a fully integrated barrier whose effectiveness is a function of detection, actuation, the available extinguishing agent, the hydraulic distribution, the exposure geometry and the human response. This applies across the board in a Saudi EPC project in the processing units, the utility corridors, the warehouses and the temporary construction. A successful acceptance test witnessed in the field can co-exist with a number of potential vulnerabilities which may have been introduced at a later stage through valve isolation, change of storage configuration, blockage of the discharge path or simply through the failure to pass on the right information. A review of advanced suppression equipment must look at the integrity of the whole performance chain and not simply assume that the digital representation is a guarantee of performance.

Recent fire management research has demonstrated the value of dynamic information. Jiang et al. (2023) combined a building fire protection ontology with time-varying sensor data and rule-based control. Almatared et al. (2024) identified the barriers to integration, competence and trust in the context of facility fire safety. Zhang et al. (2024) looked at the integration of tunnel sensing, fire prediction and 3D representation. Xie et al. (2025) took this further by looking at near real-time forecasting in a full scale building. All of these papers point to the importance of time-sensitive representations, although they do not in any way establish the reliability of an industrial foam proportioner, a clean agent release sequence or a deluge network.

Suppression experiments do of course introduce a necessary correction to any purely informational approach. Hamzehpour et al. (2023) found large obstructions to be detrimental to the tested mist configurations. Moinuddin et al. (2024) looked at hydrocarbon fire suppression in enclosures. Robinet et al. (2022) highlighted the importance of physical sensitivity analysis and Noda et al. (2021) found a significant discrepancy between the measured spray cooling and the numerical predictions. A digital twin should therefore be assessed in terms of its ability to reproduce suppression behaviour of relevance to decisions within the stated uncertainty rather than on the basis of the interface's sophistication.

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The existing literature contains a number of definitions of the digital twin, some discussion of operational risk and some on construction safety (Sharma et al., 2022; Zio and Miqueles, 2024; Han et al., 2025). The more specific issue of how an EPC contractor can establish, maintain and improve the evidence of suppression performance throughout design, commissioning and operation is still not adequately addressed. This paper seeks to fill that gap through a critical review and the proposal of a verification-led implementation framework.

2 Study aim, objectives and boundaries

The aim of this review is to assess how synchronised digital representations can support credible performance testing and constrained optimisation of advanced fire suppression systems across the lifecycle of Saudi industrial EPC assets. The objectives are to establish the physical parameters which determine the success of suppression; to differentiate between predictive twins and static records; to assess the type of test evidence and the level of uncertainty controls which are appropriate; to map out the responsibilities for implementation across the EPC handover; and to identify the research questions which will require field validation. This is not a review of emergency navigation or sustainability in the broad sense. The unit of analysis is the installed suppression system and its ability to perform.

The review looks at water mist, sprinklers, deluge systems, fixed gas systems and the various foam related systems at the level of equipment states and performance requirements. The detailed experimental synthesis is focused on water sprays and mists as these are the most directly relevant and we have the strongest body of recent, traceable evidence in that area. The conclusions are therefore not to be generalised to other extinguishing agents which have not been tested. Saudi applicability is treated as an engineering transfer issue rather than as evidence of a Saudi deployment or experiment having taken place.

3 Review design and evidence appraisal

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A systematic integrative review was chosen as the approach as the question cuts across experimental fire science, computational modelling, asset information and construction governance. It's an exercise in explanatory synthesis rather than one in pooled estimation of a common treatment effect. The material was drawn from the three provided reference papers and from publisher and research index records using combinations of the terms: digital twin, fire suppression, fire protection, water mist, performance validation, construction safety, industrial maintenance and uncertainty. The time period for inclusion was publications from 2020 to 2025 and each of the 30 included references has a DOI which maps to a publication record in the database. The 2026 paper was used for architectural comparison and was not part of the evidence base for the time period.

Screening was done on journal papers with a clear link to at least one of the four domains: actual suppression performance, fire scene sensing, twin credibility or asset lifecycle information. Papers solely on evacuation were only included if they provided some insight into data coupling or decision support. Conceptual work was assessed on the basis of its explanatory power and the operational assumptions it made. Experimental work was assessed on test configuration, observable results and stated limitations. Computational work was assessed on calibration, benchmarking and sensitivity to the various modelling choices. This approach ensures that a survey, a validated experiment and a proposed architecture are not all treated as equivalent forms of evidence.

Evidence was coded thematically by hazard, protected asset, data source, numerical representation, performance criterion, uncertainty treatment and lifecycle stage. Contradictions were kept as they were (not averaged). For instance a numerical model might be able to reproduce the temperature trend but not the radiative cooling, in which case the validation would be contingent on the decision at hand (Noda et al., 2021). There are no database wide hit counts, no claims of exhaustive coverage and no assertion of any unpublished Saudi performance data. This is a very transparent critical review of a deliberately assembled, DOI-traceable corpus and

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is not a statistical meta-analysis. The conclusions are therefore about the strength and transferability of the evidence rather than about estimated population effects.

4 From equipment records to an operational twin

The distinction between a digital model and a digital twin is very important. An as-built drawing will contain the geometry and a supervisory dashboard will contain the measurements. Neither of those by themselves is a continuously reconciled representation of the equipment's behaviour. Sharma et al (2022) point to the importance of domain specific architecture and the lack of any consistent credibility metrics. For suppression assets the minimal twin consists of a configuration baseline, time stamped observations, a testable physical response model, documented uncertainty and a controlled path from diagnosis to maintenance action. Asset identity must survive vendor data import, commissioning changes and component replacement.

The architecture shown in Figure 1 has the field devices beneath a semantic equipment layer. The inputs are fairly standard: pump suction and discharge pressure, flow, tank level, valve position, nozzle family, agent inventory, release panel events, detector health and environmental state. The physics layer will do the hydraulic delivery and agent transport estimation. The scenario layer will look at obstruction, fire size and ventilation. The decision layer will provide the performance margins and evidential confidence. This is essentially the information fusion logic of Jiang et al. (2023) re-configured to prevent any automated action where the model doesn't have its own independent assurance.

Construction literature abounds with references to the difficulties of achieving synchronisation. Tuhaise et al. (2023) point to the difficulty of linking together the various built environment data sources; Hosamo et al. (2022) talk about the issue of standardisation of information; Hakimi et al. (2024) look at the facility management use case. In the EPC world the issues of tag number consistency, revision control and responsibility for sensor calibration can be more important than

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the visual detail. An update to the nozzle layout should trigger a traceable model revision and a new applicability assessment rather than simply silently overwrite the approved commissioning baseline.

Digital continuity also has a temporal aspect. Lugaresi et al. (2023) talk about the online comparison of simulated and actual sequences, while Hassan et al. (2024) look at the practicalities of maintenance deployment. A good system must be able to identify stale telemetry, missing values and instrumentation faults prior to treating an apparent pressure deficit as a mechanical deficiency. If the synchronisation fails the twin should simply enter a reduced confidence state rather than go on and issue its optimised settings from what is effectively stale information.



Figure 1. Conceptual, verification-led digital twin architecture for installed fire suppression equipment. Arrows represent ordered assurance activities, not automatic control signals.

5 Performance mechanisms and testing requirements

You can't work out suppression success from a single discharge pressure. In water systems pressure affects the flow and the droplet formation; nozzle orientation and ventilation will affect the transport; heat release, ceiling shape and shielding will all affect the amount of extinguishing medium that actually gets to the flame or fuel. Tanaka et al. (2020) showed that scale model similarity can be lost if the spray mass flux distribution isn't maintained. Liu et al. (2022) looked at the sensitivity to drag and to the numerical spray parameters and that work again underpins the need to check the computational representation is valid before you apply it to a new installation.

The appropriate outcome will of course depend on the design intent. For a suppression system the relevant outcomes might be reduction in heat release rate, flame extinction, gas temperature, thermal exposure and re-ignition. For a protection or control system the acceptable endpoint may be containment, cooling of the equipment or prevention of escalation. Hopkin et al. (2022) looked at how the performance of an electronically controlled mist can be derived from fire test data. Kraus-Namroży and Brzezińska (2022) looked at nozzle effectiveness. Santangelo et al. (2022) used full scale tests in a specific enclosure application. These examples highlight the variety of possible test endpoints and the fact that a single success score is not going to be appropriate.

Industrial fire layouts make obstruction the key issue. Hamzehpour et al (2023) identified nozzle dependent limits under shielded conditions, demonstrating that a sufficient nominal capacity does not necessarily result in agent penetration. Moinuddin et al (2024) have done a direct comparison of experimental and numerical approaches for hydrocarbon fires which is of course relevant to a number of industrial hazards. A credible twin would therefore have to treat obstruction, leakage and ventilation as state variables rather than just as fixed drawing annotations. If the hazard geometry is changing as a result of construction or plant modification then the valid operating envelope will need to be re-evaluated.

Table 1 then takes those findings and puts them into an equipment based test matrix. It deliberately separates out the observed variables from the acceptance evidence. An inferred

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performance margin may be of some assistance in terms of prioritisation but in no way can it take the place of the prescribed witnessed tests, certification or engineering approval. The performance criteria should be established against the project design basis and the applicable authority requirements, not against some performance criteria which has been invented by an optimisation algorithm.

Table 1. Equipment-centred evidence and off-design testing matrix synthesized from recent suppression research.

Equipment / function	Observable evidence	Failure or off-design test	Interpretive limit
Pump and feed network	Pressure, flow, duty/standby transition	Partly isolated valve; degraded duty pump	Nominal pressure alone cannot prove distribution
Mist / deluge nozzles	Flux, spray pattern, actuation time	Shielding, shifted geometry, ventilation	Validated nozzle family and hazard required
Agent storage / release	Inventory, concentration or delivery status	Leakage, actuator delay, release interlock	No extrapolation across different agents
Detection and controls	Event logs, response latency, signal health	Sensor fault; network loss; inhibited circuit	Control proof is not extinction proof
Integrated installed system	Witnessed tests and revision-controlled records	Concurrent impairment and scenario variation	Approval limited to tested operating envelope

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6 Credibility, calibration and uncertainty

Twin credibility is conditional in that a model which has been verified for nominal hydraulic flow may well not be predictive in respect of droplet evaporation, smoke movement or extinction. Shao et al. (2023) make the point that verification, validation and uncertainty quantification should be in place as part of the model use. The same is absolutely true of fire protection where the potential consequence of over confidence may be vastly out of proportion to an apparently small modelling error. An acceptance report should therefore state the claim being tested, the sensors which are to support it, the operating envelope which is acceptable and the consequence of a failed check.

A staged approach is proposed. First, check dimensional and logical correctness against the approved equipment schedules, instrument ranges and control narratives. Second, validate the individual components using calibrated flow, pressure and actuation data. Third, test the interacting subsystems (standby pump changeover, valve response, alarm to release timing etc). Fourth, where possible compare the predicted scenarios against independent fire test benchmarks. Finally, run the model in shadow mode, logging the advisory predictions without any change to the suppression controls until the performance and governance criteria are met.

The evidence is consistent with disciplined scepticism. Noda et al (2021) saw a large difference between predicted and measured cooling in their setup and Robinet et al (2022) showed sensitivity to suppression parameters. Agreement on one observable should not be presented as evidence of global model validation. The sources of uncertainty are sensor drift, fuel characterisation, ventilation, nozzle wear, mesh resolution, turbulence modelling and human induced changes to the equipment configuration. Any prediction that is reported should be accompanied by a confidence interval or a justified scenario band and should state the most significant assumptions.

Testing also requires a clear separation between physical commissioning and virtual experimentation. Somers et al. (2023) found that in many digital twin testing applications passive evaluation is the norm. The proposed approach is one that supplements rather than replaces physical inspection, discharge testing and maintenance. If a prediction is outside of the defined error tolerance then the model loses its approval for that decision until it is recalibrated. Importantly a low error historical fit is no guarantee of safe extrapolation beyond the scenarios in which the model was assessed.

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7 Constrained optimization and decision governance

Optimisation should be aimed at minimising the loss of protection subject to mandatory hydraulic, electrical, mechanical and regulatory constraints. The variables to be optimised could be test frequency, inspection priority, spare part allocation, nozzle configuration during a redesign or the order in which you go about investigating suspected degradation. In a live safety system you would not be in a position to autonomously change discharge parameters unless that was specifically engineered and approved. Grieves (2023) links virtual testing to product assurance and the corresponding suppression principle is to perform virtual evaluation of the candidate improvement, confirm it in the physical world and then release it via the management of change process.

A multi-criteria objective can be used to balance suppression effectiveness, water or agent usage, availability, test downtime and lifecycle cost. Life safety and design basis performance must be hard constraints rather than soft objectives which can be weighted. A Pareto frontier is only of use once the infeasible and unverified configurations have been filtered out. Meza et al. (2024) describe integrated industrial twin tools, Knebel et al. (2023) point to the practical cloud and edge limitations in oil and gas. The upshot is that you end up with a preference for local, resilient monitoring for the key protection functions and a very carefully managed data exchange for the higher level analytics.

Figure 2 shows a decision sequence that maintains independence between the prediction and the authorisation. Model disagreement, missing telemetry or uncertain agent delivery would all be reasons for investigation rather than reasons to automatically relax a protective threshold. Zio and Miqueles (2024) also point to unresolved reliability and cybersecurity issues in the safety twins. Operators therefore need clear status indicators: verified, conditionally applicable, out of scope and unavailable. The interface should make it clear why a recommendation has been generated, what the basis of that recommendation is and who is responsible for carrying it out.

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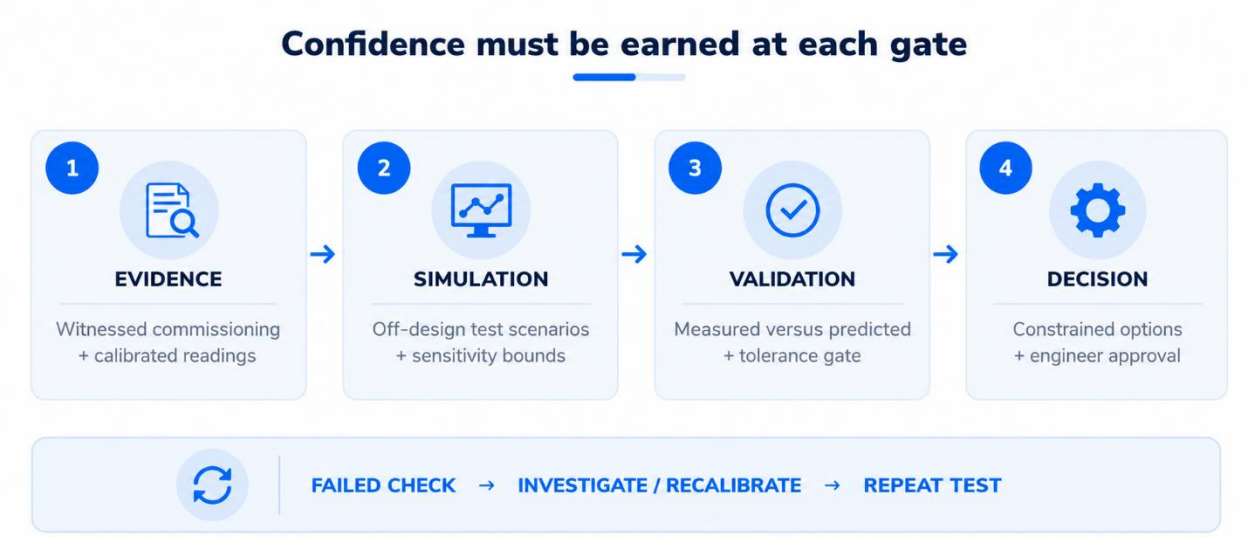


Figure 2. Proposed staged testing and optimization workflow. A failed credibility gate stops progression; no performance values are implied.

8 Saudi industrial EPC applicability

Saudi industrial EPC installations typically involve a mix of new construction and live plant interfaces, long procurement chains and a host of different equipment suppliers. Implementation should therefore start prior to mechanical completion. Engineering will need to establish a controlled correlation between the hazard scenarios, equipment tags, the cause and effect logic and the required performance tests. Procurement will need to request machine readable vendor curves, material compatibility data and instrument calibration records. Construction will need to document all physical deviations from design including pipe routing, nozzle locations and any shielding introduced by supports or cable trays. Commissioning will need to return the witnessed baseline data as immutable evidence of the installed configuration.

The Saudi context also demands that the solution be defensible in terms of heat, dust, corrosion, water availability and varying levels of industrial occupancy. These are entirely reasonable site specific constraints rather than any nationally established effects that are quantified in the papers

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reviewed. The technical transfer should be based on the project hazard study and the actual local conditions that are being monitored. The petrochemical safety perspective of Jia et al. (2024) is that the technology should be integrated with the human and organisational factors. Luo et al. (2024) similarly point to the wider role of twins in construction safety as a decision support tool. Neither of those papers in any way suggests that the responsible fire engineer or the commissioning authority can be replaced by automated recommendations.

A practical handover package would include the approved design assumptions, the tagged equipment inventories, the executable calculation models, the calibration histories, the fire test links, the scenario limitations and the model ownership. The contract would have to specify who is permitted to go and make changes to the twin following the replacement of a pump, an instrument or a nozzle and what the evidence would be for re-approval. The design would have segregated access, cyber event logging and a clear safe fallback in the event that the analytic service fails. All of this is consistent with the high consequence nature of suppression equipment and ensures that you're not reliant on a single software vendor.

9 Critical synthesis and unresolved evidence

Three takeaways from the body of work. Firstly, the fire suppression physics itself is demonstrably more mature than the integrated industrial twin validation. The experimental work provides the actual physics and the benchmarks against which to measure things, whereas a lot of the digitisation work is just about information sharing and fire visualisation. Secondly, twin validity is scenario specific. Evidence of validity obtained in the case of an unobstructed, well ventilated test cannot be assumed to be valid in the case of a shielded hydrocarbon hazard or a different nozzle configuration. Thirdly, installation records and governance are part of the technical performance. If you have the wrong asset identity or you've got an unapproved model revision then you've got a corrupted calculation regardless of how good the model is.

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The assessment in Table 2 separates out the findings which are supported from those which are assertions that would require further research. Ali et al. (2025) look at digital continuity and lifecycle sustainability, with circularity benefits being of secondary importance to the current safety issue. Han et al. (2025) do point to a wider shift in the construction safety field from monitoring to prediction; the outstanding issue is whether suppression predictions remain well calibrated as the equipment ages, the hazards evolve and the sensor coverage becomes very sparse. Xie et al. (2025) have some very positive evidence regarding fire forecasting, though the accuracy of the forecast is not the same as the accuracy of agent delivery or extinction.

The review is of course limited by the purposive rather than the exhaustive nature of the corpus and by the unevenness of the evidence across the various suppression technologies. The proprietary acceptance records, field failure records, gas agent discharge records and the Saudi site data were not available for independent assessment. The proposed framework is therefore a synthesis and a testing proposition rather than a validated performance improvement or a cost saving. That is a key boundary for the reader and for the engineer.

Table 2. Critical evidence synthesis and limits on industrial transferability.

Literature stream	What the evidence supports	What remains unverified for EPC practice
Suppression experiments	Physical effects of flux, obstruction and enclosure conditions	Transfer to differing fuel packages and vendor installations
Fire-oriented digital twins	Sensor integration, scene representation and forecasting	Confirmed agent delivery and industrial system dependability
Model credibility studies	Verification, calibration and online model checking	Standard acceptance tolerances across suppression technologies

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Construction / maintenance twins	Lifecycle information continuity and diagnostic opportunities	Ownership, cyber-resilience and adoption after EPC handover

10 Research agenda

Future work should be to conduct paired measurement and simulation campaigns on representative industrial suppression assemblies with independently witnessed baseline and off-design tests. The key areas of focus should be fault injection studies (for partially closed valves and degraded pumps), high temperature and dust exposure sensor reliability, shielded hydrocarbon fire benchmarks, detection to discharge latency and cross vendor semantic compatibility. The evaluation should be against a synchronized twin and use a set of pre-defined metrics (false alarm rate, prediction error, time to detect impairment and number of correctly identified unsafe configurations) to assess the performance.

Multisite transfer tests should look at whether a model that has been calibrated at one site is still valid when installed hardware, fire load or ventilation has changed. The research should publish uncertainty budgets, negative results and software revision histories rather than just the pretty demonstrations. Operational studies should also look at the impact of advisory systems on training and workload. That work could go some way to answering the question of whether greater data availability actually leads to more reliable protection or just more confident dashboards.

The implementation path should also separate configuration changes from operational variations. A transient drop in flow may be attributable to test demand, whereas a permanent relocation of a nozzle is a change to the underlying hydraulic and geometric assumptions of the design model. Each digital record must therefore contain the measurement time, instrument status, engineering revision and the name of the approver. Sun and Liu (2022) show the potential for linking

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construction information with dispatch decisions, but with a fire suppression twin there is a need for some degree of assurance as a bad recommendation could in fact undermine a protection. The verification records must be readable in isolation of the software that produced them, enabling the asset owner to reconstitute the accepted configuration at the end of the contract. At the research level the evaluation protocols should report performance separately for nominal operation, credible single impairments and concurrent disturbances. The metrics should include pressure and flow error, forecast calibration, missed impairment rate, nuisance alert burden and the time to restore confidence following a model discrepancy. Testing should include the adverse case of data latency occurring at the same time as a partially blocked nozzle. Such cases will reveal whether the twin is able to identify its own limitations. A model that appears to be working perfectly and continues to issue recommendations during loss of synchronisation may be less useful than a simpler model which is able to recognise that there is insufficient evidence and requests for inspection.

11 Conclusions

Digital twins provide a coherent methodology for linking suppression engineering, condition monitoring and lifecycle decisions. Their value is predicated on the use of physically sound models and independently established credibility. Recent fire tests have shown that nozzle behaviour, the degree of obstruction, heat transfer and boundary conditions can all have a bearing on whether equipment that is nominally adequate will in fact control a hazard. Digital twin research has clearly demonstrated the feasibility of sensing, semantic integration and predictive visualisation. There is however still very limited evidence of end-to-end validated industrial suppression digital twins. The architecture proposed therefore places a strong emphasis on witnessed commissioning baselines, scenario specific validation, disclosure of uncertainty, controlled optimisation and accountable human approval. For the Saudi industrial EPC projects the near term opportunity is not in automatic firefighting control but in establishing a defensible chain of evidence from the design assumptions through to the installed performance and any subsequent changes. Publication quality assessment in this area will now require field measured demonstrations, explicit failure criteria and transparently defined transferability limits.

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