Global Academic Journal of Economics and Business

Available online at https://www.gajrc.com
DOI: https://doi.org/10.36348/gajeb.2026.v08i06.013

OPEN ACCESS



ISSN: 2706-9001 (P)
ISSN: 2707-2584 (O)

Original Research Article

Smart Manufacturing of Industrial Fire Detection and Suppression Equipment: An Industry 4.0 Transformation Framework for Saudi Arabia

Waheed Mahboob Jilani[1]*, Talha Umar Khan[1]
[1]Independent Researcher

***Corresponding Author**
Waheed Mahboob Jilani
Independent Researcher

Article History
Received: 09.09.2026
Accepted: 02.11.2026
Published: 03.11.2026

Abstract: Industrial fire detection and suppression equipment is in a very odd position in the context of smart manufacturing. You have to improve throughput and traceability but you absolutely cannot compromise the independent evidence that is required to demonstrate the safety-critical performance of the equipment. This review looks at how Industry 4.0 technologies can be applied to the engineering, fabrication, assembly, verification and lifecycle support of detectors, fire alarm control panels, extinguishing valves and all the associated suppression hardware in the Kingdom. It is a critical review of the peer-reviewed literature published between 2020 and 2025 with an emphasis on digital twins, industrial connectivity, automated inspection, fire sensing and the wider context of industrial transformation. It is not a case of equating digitalisation with safety. The review makes a clear distinction between production process intelligence and product function assurance and identifies five such capabilities: a requirements controlled digital thread, instrumented fabrication, risk sensitive quality analytics, independent safety verification and post delivery learning. A six stage transformation framework is proposed which embeds regulatory evidence and human authority at all stages of the process. The argument is that Saudi manufacturers should put in place interoperable product records and validated end of line test results before they go any further and start to deploy adaptive optimisation at scale. Testable indicators are provided and a staged implementation pathway is outlined. The output is a product specific, safety governed account of smart manufacturing rather than an empirical claim that the framework has in fact improved the performance of any fire system.

Keywords: Industry 4.0, Smart Manufacturing, Fire Detection Systems, Fire Suppression Systems, Industrial Safety, Digital Twins.

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1. INTRODUCTION

The importance of industrial fire protection equipment goes far beyond the market for individual items. Smoke and heat detectors, alarm interface modules, control panels, sprinkler systems, agent release controls and extinguishing system valves are all expected to perform when things go wrong, often after a period of prolonged inactivity. The manufacturers of these items therefore have a two-fold responsibility: to be able to respond to demand more rapidly and to maintain the confidence that each configuration they supply will in fact perform its intended protective role. Standard production

Citation: Jilani, W. M., & Khan, T. U. (2026). Smart Manufacturing of Industrial Fire Detection and Suppression Equipment: An Industry 4.0 Transformation Framework for Saudi Arabia. *Glob Acad J Econ Buss, 8*(6), 2073-2083.
https://doi.org/10.36348/gajeb.2026.v08i06.013

metrics such as cycle time or output per shift are simply not adequate to capture this responsibility. A factory which is digitally efficient and yet delivers a sensor that is incorrectly calibrated or a valve that has not been properly tested has not in any meaningful sense achieved a credible transformation.

Industry 4.0 is about connecting industrial equipment, production records and computational models in order to make better decisions throughout the manufacturing lifecycle. Lu *et al*., (2020) link the aspiration to interoperable automation and end-to-end integration, He and Bai (2021) point to the importance of connected product and process knowledge for sustainable manufacturing. The reality is that these broad principles need to be substantially modified in the case of a safety-critical product. A defect can be latent for a very long time and a bad digital measurement can easily be propagated into a complete quality record. The real issue isn't whether a fire equipment factory can be connected, it's how the connected processes can generate more robust and verifiable evidence of conformity.

Saudi Arabia is a relevant case in point as industrial localisation and the development of digital capability are key components of its economic diversification strategy. A national strategy in itself won't necessarily resolve the issues of integration for a manufacturer. Alsaadi (2022) highlights the organisational and operational impediments to the adoption of manufacturing technology and Sarfraz *et al*., (2024) show that digitalisation and circularity do not necessarily progress in a uniform way across different industrial settings. This underlines the need to be cautious about simply transferring a high investment factory model to a much smaller producer of fire protection hardware. A sensible pathway to transition would need to take into account the mix of automation maturity, the use of imported components, the range of production volumes and the reliance on external certification.

The purpose of this review is to develop a safety-led framework for the Industry 4.0 transformation of the manufacture of industrial fire detection and suppression equipment in Saudi Arabia. The review is structured around four objectives: to identify the specific technical requirements of the various equipment families; to assess the extent to which the various digital manufacturing capabilities are able to meet those requirements; to define a traceable architecture which links design, manufacture and independent verification; and to establish the order of adoption and the research propositions which can be evaluated. The key contribution is a manufacturing focused synthesis rather than another review of the various algorithms that can be used to detect a real fire. Digital intelligence is treated as a tool of manufacturing control, with physical qualification, competent engineering judgement and documented release all remaining as distinct and necessary requirements.

2. REVIEW METHODOLOGY

A critical narrative review was selected as the structure as the research question spans a number of different evidential domains. The literature includes conceptual manufacturing architectures, factory demonstrations, quality control reviews, sensor and algorithm studies and assessments of industrial readiness. The outcomes, intervention units and test conditions are simply too disparate to allow for any meaningful statistical pooling. The approach is therefore to look for analytical coherence between the technologies and the manufacturing requirements rather than to produce some aggregate estimate of performance. This is a crucial distinction: the review is building and critiquing a framework rather than reporting on a new factory trial or a representative survey of Saudi producers.

The evidence boundary was set at English language journal papers published between Jan 2020 and Dec 2025. The relevant themes were smart manufacturing, industrial digital twins, automated quality assurance, traceability, sensor fusion, fire warning reliability, industrial cybersecurity and Saudi manufacturing. The search expressions were conceptually a combination of terms such as "digital twin" AND "manufacturing", "zero defect" AND "inspection", "fire detection" AND "multi sensor", and "Saudi Arabia" AND "Industry 4.0". The candidate sources were identified via the available bibliographic and publisher records and citation chaining from the background papers provided. The three papers provided in the background were used to inform the organisational model and technology scope; the two 2026 papers from those sources were not included as they are out of date (i.e. they are outside the evidence boundary).

Inclusion was predicated on a clear link to at least one of the four review questions: what information needs to flow between design and production; which processes would benefit from industrial sensing or analytics; how fire product performance should be validated; and what the constraints would be on deployment in Saudi Arabia. Preference was given to papers that reported on a specific architecture, a defined evaluation methodology, documented industrial application or a critical appraisal of the limitations. Papers which were simply about an application that wasn't in any way transferable to a manufacturing context were not considered to be of sufficient value. The citation

base consists of 30 dated sources with DOIs. No unverified screening totals, effect sizes or quantitative evidence weights are claimed as we did not have a reproducible database export and no record of independent double screening.

For synthesis each source was conceptually coded by application scale, physical asset, decision function, data requirements, validation method, safety relevance and transferability. The claims were then compared across product engineering, factory operations, acceptance testing and lifecycle support. Where the evidence was from building fire detection rather than from equipment manufacture the inference was classified as transferable design knowledge rather than as evidence of factory benefit. This is the approach to framework building that is underpinned by the critical distinction between technological promise and demonstrated industrial functionality as highlighted by Böttjer *et al*., (2023) and Bitencourt *et al.,* (2025). Table 1 sets out the principal evidence streams and their boundaries.

Table 1: Evidence streams informing the manufacturing transformation framework; interpretations are specific to fire-protection equipment

Evidence stream	Representative studies	Transferable contribution	Critical limitation
Architecture / interoperability	Lu *et al*., (2020); Schlemitz and Mezhuyev (2024)	Common data models and interface discipline	Connectivity alone does not validate a fire product
Product–process digital twins	He and Bai (2021); Böttjer *et al*., (2023)	Model-based monitoring and reconfiguration	Fidelity and external validation remain context-dependent
In-line quality assurance	Azamfirei *et al*., (2023); Markatos and Mousavi (2023)	Inspection feedback and process deviation detection	Algorithmic scores cannot replace approved test limits
Fire sensing and decision logic	Baek *et al*., (2021); Cheng *et al*., (2024)	Temporal fusion and scenario-based challenge testing	Performance evidence comes mainly from use environments
Saudi industrial transition	Alsaadi (2022); Sarfraz *et al*., (2024)	Staged capability development and supplier coordination	No direct plant-level causal estimate for this equipment
Resource and lifecycle learning	Turan *et al*., (2022); Timperi *et al*., (2024)	Material accountability and field-to-design feedback	Recovered components may require explicit requalification

Evidence interpretation needed to be mindful of reporting quality. A lab classifier evaluated on balanced examples is not something that can be fairly compared to a factory system which would have been evaluated across a range of suppliers and production shifts. A demonstration of reduced resource use in no way provides evidence of compliance with functional safety requirements. Each result was assessed in the context of its experimental boundary, the availability of reference measurements and the level of human involvement. Contradictory results were not coerced into a single effectiveness estimate. The approach was one that preferred an explanatory synthesis in which omissions, implementation dependencies and negative evidence were all visible. It was important where the precision of the reported accuracy figures actually masked a very incomplete picture of the failure scenarios.

3. PRODUCT-SPECIFIC MANUFACTURING REQUIREMENTS

Fire detection and suppression equipment is not one single manufacturing category. Optical smoke detectors are an assembly of chambers, light sources, electronics and embedded signal processing. Heat detectors are based on a repeatable thermal response. Control panels are a combination of power management, supervised circuits, communications and configuration software. Suppression valves and actuators have their own set of mechanical tolerances, sealing behaviour, pressure integrity and actuation characteristics. Assemblies which contain cylinders, piping interfaces or release mechanisms all have additional requirements relating to material identification, assembly torque and leakage. Each family will therefore have its own critical to quality characteristics even if the same enterprise software is being used.

For detectors you have variation in the incoming component, optical contamination, solder defects and firmware configuration all of which can affect the measured response. For a control panel you can have mismatched terminal assignments, batteries behaving in an unsuitable manner or just plain incomplete software regression testing and that can all lead to an otherwise perfectly acceptable visual inspection being compromised. With valves and release mechanisms it's not just a case of

dimensional conformance that will give you leak tightness or repeatable operation under the expected conditions. The differences are such that product classification is a prerequisite to digital transformation. A single dashboard reporting a generic pass percentage could be masking the difference between a cosmetic reject, a performance reject and a reject which is in fact relevant to the emergency response.

The fire detection literature is full of examples of why you need multiple dimensions of evidence. Wu *et al*., (2021) look at the fusion of smoke, temperature and gas signals. Li and Liu (2022) look at multi-sensor fire alarm classification. Baek *et al*., (2021) go further and show the importance of the temporal relationships between the various sensors. All of these are studies of detection logic rather than the manufacturing yield of the commercial devices. The lesson that can be transferred is that the factory acceptance test should be looking at the device's response to relevant stimulus sequences and nuisance conditions rather than just a single threshold reading. Gaur *et al*., (2023) also show that electrical and visual indications can be complementary to one another, though they don't in any way prove that their proposed architecture meets all the certification requirements.

A product-centric digital thread should therefore link the approved design revision to component provenance, assembly operations, firmware checksum, calibration references, test conditions, deviations and final authorisation. A unique serial number is only of value if that identity persists through rework, line changes and component substitution. Onaji *et al*., (2022) address the wider issue of design to production integration, and Fu *et al.,* (2022) point to the value of the lifecycle in terms of linking the manufacturing information to the later maintenance phase. For fire protection equipment the key extension is the ability to trace from a field reported functional issue back to the relevant bill of materials and process history.

Product genealogy is a configuration management issue. A detector may have a number of components that look the same but have different verified characteristics. A panel may be supplied with market specific software or market specific electrical interfaces. The trace records have to be able to tell the difference between an approved alternative and an unauthorised substitution. The bare minimum record would be who approved the substitution, which production orders it applied to and what verification evidence still applied. When an assembly is reworked the test result has to be recoverable rather than simply being overwritten by the pass. The event histories that are created in this way allow for root cause analysis and prevent the false impression that every unit went through the same sequence of operations.

4. INDUSTRY 4.0 ENABLERS AND TECHNICAL BOUNDARIES

An interconnected factory needs much more than just equipment with extra sensors. You need industrial gateways, PLCs, MES and enterprise planning systems to all be describing the assets and events in a consistent way. Lu *et al*., (2020) point out the significance of interoperable interfaces as opposed to just automation. Schlemitz and Mezhuyev (2024) go on to identify the collection and standardisation of data as two of the enduring challenges of smart manufacturing. A pressure reading can be stored with ease without any engineering units, instrument ID, timestamp or calibration status and yet be entirely useless for the purpose of an acceptance decision. The data models have to be designed from the quality questions first.

A practical architecture is one that decouples the shop floor execution from the analytical services. At the equipment level the stations produce the measurements and carry out the controlled operations. At the operations level the MES links the readings to the correct serial number, operator, tool and route. At the engineering level the approved specifications and test limits are maintained under revision control. The analytics layer will detect a change in capability as it emerges but it won't go and change the design limits. Quality and compliance people then review the exceptions and authorise release. Figure 1 shows the proposed information flow including the return path for engineering changes and field feedback.

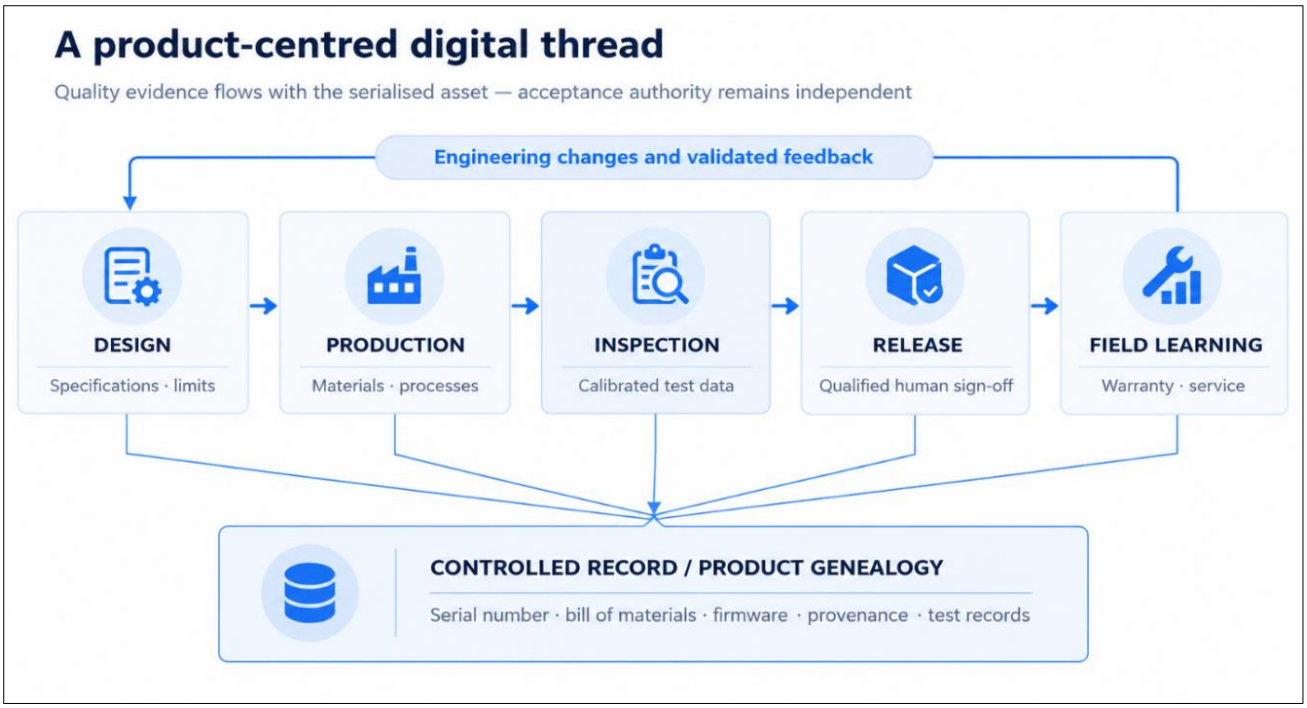


Figure 1: Proposed product-centred data architecture and engineering feedback pathways. Original conceptual synthesis

Digital twins can be of value when their level of fidelity is deliberately aligned to a particular decision. A process twin could replicate assembly sequence, buffer congestion and station utilisation. A product twin could link tolerances, calibration conditions and performance results. Soori *et al*., (2023) look at the use of digital twins for manufacturing optimisation and Javaid *et al*., (2023) provide a broad overview of the range of industrial applications. Neither the visual complexity of the model nor the frequency of its updates is in itself a guarantee of technical credibility. Böttjer *et al.,* (2023) point to real time integration and model fidelity as two major practical issues. Bitencourt *et al*., (2025) stress the importance of verification and validation as prerequisites for trustworthy use.

For a detector assembly line a light weight process twin could well be justified in terms of changes to material flow without necessarily being used to predict smoke sensitivity. For a valve station a physics based representation of pressure and leakage could be used to flag up odd test curves (again subject to checking against independent reference measurements). More sophisticated models should only be introduced where the requisite experimental data, uncertainty bounds and recalculation resources are available. The fundamental design principle is proportionality: use the simplest model that will answer a significant and testable manufacturing question and record the circumstances under which that model is not to be trusted.

Condition monitoring should be treated in the same way. Liu *et al*., (2022) point to data management, model fidelity and uncertainty as the key problems with twins in the context of machine monitoring. In a factory a warning that a test fixture is deteriorating may be sufficient to justify a service call but it would not in any way validate the quality of the units that were tested on that fixture. You need a rule to enable you to link back to the affected production intervals when instrument drift or equipment failure is confirmed. That reverse linkage is what turns predictive maintenance into a part of product assurance. Warke *et al.,* (2021) also highlight the importance of manufacturing level data integration, though their sustainability results don't provide any measure of functional safety for the products in this study.

5. INTELLIGENT INSPECTION AND SAFETY ASSURANCE

Automated optical inspection, torque monitoring, electrical test automation and sensor trend analysis can all serve to reduce the need for sporadic manual sampling. Markatos and Mousavi (2023) go on to show that Industry 4.0 quality assessment is not simply about inspection but about moving into the realm of predictive monitoring. Azamfirei *et al.,* (2023) point out that in-line inspection is only of value if the inspection is going to have an effect on the manufacturing process. Psarommatis *et al.*, (2022) take a broader view of defect prevention as part of a sustainability argument. For fire equipment in particular, rejection prediction should be used to supplement rather than

supplant the documented inspection of safety related attributes. The cost of missing a critical defect is asymmetric to the cost of the rework that would be incurred if you reject a non-critical item.

Inspection design should incorporate three levels of control. The first is deterministic checks which enforce dimensional, electrical and firmware specifications as approved. The second is trend monitoring which will flag any drift in a range of variables (e.g. leak test pressure, actuator response time, detector baseline current). The third is the use of statistical or machine learning models which will flag for engineering investigation when a combination of process signals falls outside of previously qualified patterns. These are different things. A classification score may indicate that a unit is similar to a previous failure, but that is not the same as an approved technical specification which defines acceptance. Hossain and Purdy (2024) look at the conditions for integration of zero-defect approaches and their conclusions do not in any way obviate the need to maintain transparent acceptance criteria for high consequence products.

The test design must also be able to differentiate between manufacturing conformity and fire performance certification. Production testing may be used to establish continuity, calibration, leakage and commanded valve travel. Type approval, environmental qualification, endurance testing and so on will be used to establish various aspects of the product's suitability. The certification pathways will vary by product and by destination market and will have to be established by appropriately qualified people in accordance with the relevant requirements rather than being deduced from some generic data architecture. The proposed framework therefore precludes self-modifying acceptance criteria and requires independent review in the event of any change to the algorithm, component supplier or firmware. The automated test equipment itself will require calibration, method validation and access controls.

Fire analytics are particularly susceptible to misleading transfer claims. Cheng *et al*., (2024) look at visual fire detection methods and Gragnaniello *et al.,* (2024) highlight the significance of scenario diversity and the limitations of the dataset. Miao *et al*., (2022) look at fire warning via the fusion of electrical information in substations. The detection capabilities they report are not in any way equivalent to manufacturing acceptance data as the environment under test, the ground truth and the consequences of a false alarm are all very different. What can be transferred is the experimental methodology: representative challenge conditions, a clear procedure for dealing with false alarms, robustness testing and independent evaluation on data not used in the tuning of the decision mechanism.

Measurements must be traceable through an auditable chain from the reference standard to the instrument, to the station, to the serial number, to the observation and to the disposition. Where models are providing advisory forecasts the records held should contain the model version, the input features, the confidence or uncertainty, the human response and the subsequent outcome. A digitally complete record is not in itself a valid one (missing calibration evidence or an unidentified firmware version will render it invalid). On the other hand a well designed traceability will allow you to investigate a systemic defect without having to go and recall every single product in the system. Data governance is therefore a part of engineering assurance rather than just an IT issue.

Sampling plans need to take into account the implications of different failure categories. A programme may well use statistical sampling for cosmetic attributes and unit by unit inspection for functions. That approach has to be underpinned by an engineering risk assessment and relevant product requirements, not simply because AI is 'accurate'. Liu *et al*., (2023) define Quality 4.0 as the integration of management systems and digital methods and that's a good reminder that model performance is just one element of quality governance. The approach proposed requires escalation where inspection equipment is not available. A production manager cannot just turn a lack of evidence into an acceptance in order to maintain their delivery performance.

6. SUPPRESSION EQUIPMENT AND PROCESS INTEGRITY

Suppression manufacturing is a separate issue as its main failure modes are quite different from those of electronic detectors. The valve body, the springs, the seats, the diaphragms, the solenoids, the nozzles and the pressure containing interfaces all depend on precise machining, cleanliness and assembly. The critical parameters here can be material grade, surface finish, sealing compression, torque, proof or leakage pressure, electrical actuation and response repeatability. The fact that you can digitise the assembly traveller means you can keep the records of that process linked through machining, coating, assembly and testing. That doesn't in any way obviate the need for inspection of the various failure modes that are specific to suppression manufacturing.

A good use of process analytics is the analysis of the full test trace rather than just a single endpoint. A leak test curve for instance might show unstable fixtures, thermal effects or different profiles

of pressure decay even if the individual reading is within spec. You have to have reference conditions, measurement uncertainty, known confounders and acceptance criteria in place before you can use such signatures to disposition units. Leng *et al*., (2022) show the potential for very flexible digital twin supported production arrangements but an adaptable production line still has to have the interlocks and proven test sequences in place for safety critical assemblies. Any reconfiguration must be accompanied by a formal qualification review rather than simply being a normal scheduling change.

Lifecycle information provides an additional, conditional benefit. If field maintenance is uncovering recurring actuator sticking or premature seal failure then the serial level production history may be able to identify a supplier, batch or process link. Fu *et al*., (2022) detail the general value of design, manufacture and maintenance integration. The value of such integration in this instance is predicated on the ability to distinguish between a suspected association and a proven root cause. Field failure reports are all affected by installation conditions, maintenance practices and reporting quality so these factors must be taken into account before any changes to the production controls are made. The manufacturing twin should therefore be used to preserve alternative explanations and to support testing rather than to generate unwarranted causal certainty.

7. SAUDI ARABIAN TRANSFORMATION CONTEXT

A framework for Saudi manufacturing sites must take into account business readiness as much as digital architecture. You can have a facility which runs on imported control hardware, with multilingual technical documentation, with fabrication being subcontracted and with varying degrees of process automation. Attempting to upgrade everything at the same time can result in a piecemeal data platform and a huge maintenance burden. Alsaadi (2022) points to the need for an analysis of the underlying structure to identify adoption barriers, while Sarfraz *et al*., (2024) argue that capability development needs to be coordinated as much as investment. The takeaway is that you need to sequence the reforms according to product risk and information dependency rather than simply rank the suppliers on the number of machines they are connected to.

Initial plant assessment should cover: the equipment families produced, the approval and certification responsibilities, the existing level of traceability coverage, the calibration systems, the critical outsourced processes and the current authority for engineering changes. It should be able to make the distinction between an inaccessible dataset and an unnecessary dataset. A small manufacturer may well get a greater safety benefit from disciplined serial traceability and controlled test software than from a very expensive factory wide simulation platform. The same applies to the investment decision: you have to consider workforce training, network segregation, vendor support and the availability of local metrology services. Wu *et al*., (2024) show that the trajectories of manufacturing transformation are different depending on the organisation's characteristics, which again supports the case for a context specific approach.

Cybersecurity is a particular issue as digital connectivity can open up entirely new pathways to unsafe production outcomes. A corrupted test recipe, a compromised firmware image, a forged component record or a manipulated calibration result can all have a detrimental effect on the level of assurance without the line actually stopping. Production technology and enterprise systems need to be segregated on a basis of operational need. Identities, software releases, equipment access and changes to test limits all need to be recorded and independently approved. Simply putting all the data onto a single platform is not the same as integration if the write permissions and the responsibilities associated with them are no longer clear. The fundamental principle is that analytical convenience must never take precedence over the separation of duties or the integrity of the production evidence.

Environmental arguments also need bounded claims. Turan *et al*., (2022) look at how process data and modelling can be used to improve material consumption. Timperi *et al*., (2024) look at the business and organisational factors that affect digitally enabled circular manufacturing. Ali *et al*., (2025) make the link between digital twins and resource circularity. With fire protection equipment in particular, refurbishment or material recovery cannot simply be assumed to be acceptable just because it reduces the amount of waste. Safety critical components may require explicit requalification and the recycling process itself must respect the applicable material and environmental controls. The relevant sustainability metric is the amount of waste avoided per conforming and safely releasable product, not just the amount of waste that is discarded.

Supplier development is a key consideration. Domestic assembly of imported detector modules could create jobs and lead to shorter replenishment times with the component specs still being controlled externally. Localisation should be evaluated in terms of process capability, testing capability, engineering change authority and the amount of supplier evidence available to the manufacturer. Any digital

record passed on from the supplier should contain the name of the issuing organisation and the scope of its applicability. The training required would need to cover metrology, process engineering, data stewardship and safety case preparation as well as the operation of the purchased software. These are the capabilities which are required for genuine industrial independence and for the sustainable transfer of knowledge.

8. PROPOSED SIX-STAGE TRANSFORMATION FRAMEWORK

The synthesis results in a 6-stage framework which is built around a digital thread that is evidence-bearing rather than one focused on technology acquisition. Stage 1 is the establishment of an approved product taxonomy, the critical to quality characteristics and a documented baseline of quality escapes, rework, test coverage and traceability. Stage 2 is the standardisation of serial identities, engineering units, timestamping, component genealogy and revision controlled test recipes. Stage 3 is the instrumenting of the high risk production steps with calibrated measurement and structured records. Stage 4 is the deployment of validated advisory analytics and limited scope process twins. Stage 5 is the integration of independently governed safety testing and product release. Stage 6 is the capture of authorised field feedback for periodic design and process review. It's a staged progression, but learning from later stages can expose weaknesses which will in turn require earlier controls to be modified.

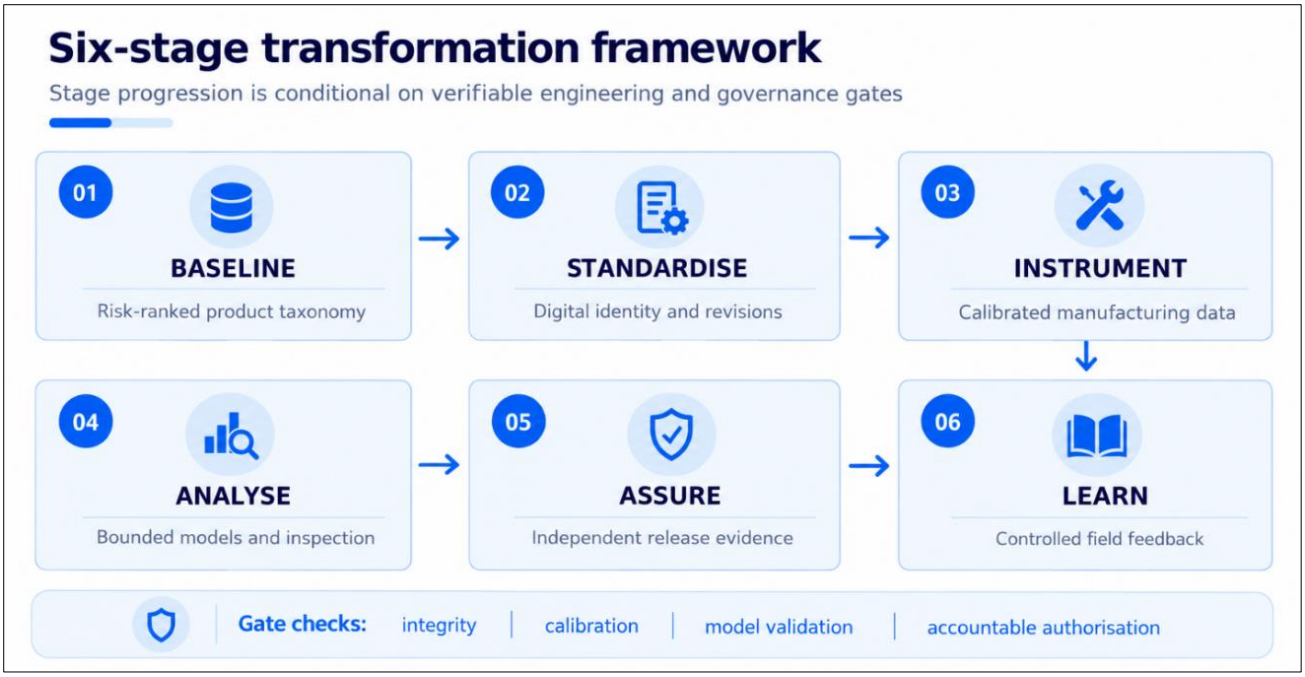


Figure 2: Six-stage pathway with mandatory evidence gates. Original conceptual synthesis

A deployment gate must be met prior to any significant transition. Baseline quality criteria need owners; data integration needs to be checked for integrity and completeness; connected equipment will require cybersecurity and calibration checks; analytic models will need out of sample testing and clear defined use boundaries; and of course release decisions will need clear accountability. Table 2 takes those requirements and turns them into actual evidence and indicators. It is a framework for the manufacturer to adapt to, not a replacement for technical standards, statutory approvals or an accredited conformity assessment. The one safeguard that it provides is that a model can flag an issue, whereas an approved specification and authorised personnel will be the ones to decide on acceptance and release.

Table 2: Stage-gate evidence requirements and proposed evaluation indicators

Stage	Control focus	Minimum evidence	Suggested indicator
1. Baseline	Product and failure-mode taxonomy	Approved critical-to-quality map; measured starting conditions	Critical defect classes agreed
2. Standardise	Serialised digital thread	Revision-linked material, firmware and test genealogy	Identity and record completeness

Stage	Control focus	Minimum evidence	Suggested indicator
3. Instrument	Calibrated station data	Reference checks, recorded tools and unit-specific readings	Measurement coverage and drift
4. Analyse	Bounded advisory analytics	Out-of-sample validation, model version and exception logging	False alarms; missed critical cases
5. Assure	Independent qualification and release	Documented criteria, approval authority and retained test evidence	Evidence completeness and escapes
6. Learn	Governed field-return analysis	Traceable investigations and approved engineering changes	Root-cause closure and response time

The implementation order also addresses the inherent tension between flexibility and standardisation. There's obviously a case for flexible manufacturing when you're producing to accommodate detector variations, different panel configurations or a range of valve sizes. On the other hand every changeover presents a potential for a recipe mismatch, wrong fixture or a retest being missed. Reconfiguration must therefore be checked against the released BOM and approved route. The system should not allow the process to start where there is a conflict in the key identifiers and should have a documented path for an override which is subject to competent approval. Automatic convenience functions are fine as long as you understand and can control the failure states.

The framework can be assessed via six propositions. A more complete component genealogy would be expected to reduce both the scope and duration of trace investigations. Having the station and calibration context recorded would be expected to improve defect attribution as opposed to just having the individual measurements. Independent verification of the analytic alerts would be expected to reduce the number of false investigations without increasing the number of critical defects that went undetected. Approved digital recipes would be expected to reduce the number of configuration errors at changeover. Process level material optimisation would be expected to reduce the amount of waste per unit of conforming output. Finally, structured field feedback would be expected to improve the specificity of the design changes. Each of these propositions would need to be tested prospectively against a defined baseline; none of them are going to be true simply because you've got connected equipment in place.

9. IMPLICATIONS, LIMITATIONS AND RESEARCH AGENDA

For the manufacturing manager the first decision is where the traceability failures are going to have the biggest impact. A risk ranked pilot could start with one detector family or one suppression valve assembly, establish end to end serial records and compare the level of test completeness before and after integration. The quality team would have to predefine the critical defect categories and be able to differentiate between a production failure and an equipment fault or a data error. The engineering team would have to maintain versioned configuration records and the info security team would have to protect the interfaces that could have an impact on the measurement or the release status. That's a far more significant arrangement than just having a modern factory dashboard on display.

For the researcher the next step is to conduct comparative multi-site studies to determine whether the framework is of value in different equipment families and in different sized facilities. Appropriate designs would be controlled before and after, interrupted time series and matched line studies (with appropriate adjustment for product mix and production volume). The outcomes would be the critical defect escape rate, measurement completeness, false rejection rate, retest burden, time to trace a bad batch and operator workload. Where serious failures are infrequent, the use of validated challenge specimens and fault insertion exercises may provide a more informative assessment than simply waiting for failures to occur. Any claims that are made as a result of the study should be accompanied by an assessment of uncertainty and should not equate correlation with causation.

Such trials should also reveal the excluded failures and the unresolved operational anomalies.

The review is of course limited. The 30 reference synthesis covers adjacent areas of manufacturing and fire detection but doesn't establish that all of the results cited are applicable to Saudi fire equipment manufacturing. There is no primary plant data, no stakeholder interviews, no experimentally validated architecture and no formal census of the literature. A number of the technologies have been looked at in other manufacturing contexts so there is a transferability issue which can only be resolved through product specific trials. The evidence base is therefore to be read as a considered engineering proposition rather than as a performance assessment at national level or as an assurance of compliance with certification.

A good future experiment would be to run two lines of the same approved equipment family,

one introducing structured digital genealogy and the other continuing with the existing documentation. The trial would have a clearly defined observation period, a defined product mix, defined test methods and a defined approach to rework. You could then go on to assess the amount of missing evidence, the number of changeover errors, the time taken to investigate a trace and the cost of quality with confidence intervals. A second experiment could look at whether advisory anomaly detection leads to any improvement in defect investigation without in any way changing the formal release decision. The publication of a failed deployment, the publication of model drift and the publication of integration costs would be just as informative as the publication of a successful pilot as it would provide a real insight into the actual conditions under which adoption would occur.

10. CONCLUSION

Smart manufacturing can be a real enabler for the fire protection equipment sector in Saudi Arabia if we treat digital transformation as an engineering assurance problem. The literature reviewed confirms the value of interoperable production records, well bounded digital twins, risk sensitive inspection and better integration of manufacturing with lifecycle information. It provides no support for the more ambitious view that predictive models, connected machines or virtual testing can in fact replace physical product conformity. Detectors, alarm panels and suppression assemblies all have their own set of critical to quality attributes which will require different validation methods, secure configuration control and competent release authority. The proposed six stage framework takes those requirements and turns them into a practical pathway from product taxonomy to field learning. The value of the framework will be determined by the evidence generated during the plant level trials, particularly the evidence on critical defects, traceability, configuration integrity and the safety of the automated decisions. The success of the transition will therefore not be measured by how digitally intensive the process is, but by whether the manufacturers can in fact produce consistently, independently defensible and traceable fire protection equipment at an industrial scale.

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