© SEP 2026 | IRE Journals | Volume 10 Issue 3 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV10I3-1722785

Smart Instrumentation and Advanced Process Control for Improving Reliability and Operational Efficiency in Saudi Oil and Gas Facilities under Vision 2030

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Abstract- Saudi oil and gas facilities have reached a stage where they must improve production continuity, energy efficiency, asset integrity, and emissions performance simultaneously. This study considers how smart instrumentation and advanced process control can be combined to create an operating approach that is focused on reliability, rather than being presented as separate digital projects. It reviews the literature published between 2020 and 2025 on intelligent sensors, Industrial Internet of Things connectivity, soft sensing, fault diagnosis, predictive maintenance, digital twins, model predictive control, nonlinear and economic predictive control, and real-time optimisation, with a specific emphasis on upstream production, gas compression, processing and refining. Instrumentation quality influences the amount of useful information available to higher levels of control, and advanced control uses this verified information to generate coordinated actions that reduce process variability, prevent equipment from operating in harmful areas, and utilise capacity within safe limits. Research in the oil and gas industry has produced positive results in machine-learning-based fault detection, self-diagnosis of multiphase meters, compressor control, gas-lift stabilisation, and health-aware optimisation. Further evidence from Saudi Arabia, based on facilities that have undergone digital transformation, also demonstrates the strategic value of large-scale sensing and closed-loop optimisation. The paper proposes an integrated Sense-Validate-Predict-Optimize-Act-Learn architecture, along with a five-stage implementation plan aligned with Vision 2030. The key conclusion is that the greatest reliability benefits are achieved when instrument assurance, analytics, process control, maintenance, cybersecurity, and workforce governance are designed as part of a single lifecycle system.

I. INTRODUCTION

The oil and gas industry in Saudi Arabia still plays a vital role in meeting the nation's energy needs, bringing in export revenue, supplying industrial feedstocks, and financing its economic diversification programme. Vision 2030 does not mean that hydrocarbon-based facilities will become less important; instead, it puts more pressure on them to achieve higher productivity, lower resource intensity, better safety records, and greater technological development. As part of the national programme for transformation, digital infrastructure, artificial intelligence, cybersecurity, and industrial innovation are seen as factors which contribute to competitiveness [1], [2]. The present situation has therefore given rise to a practical engineering problem for both brownfield and greenfield sites: which digital capabilities actually improve the dependability and performance of physical production systems, and how should they be integrated into existing process-control and maintenance practices?

A key solution is smart instrumentation because all kinds of optimisation, diagnostic, and predictive applications depend on accurate process measurements. Modern field devices have gone past standard measurements of pressure, temperature, level, flow, vibration, composition, valve position, and electrical variables by adding digital diagnostics, condition indicators, local computing, time synchronisation, and network connectivity. Industrial analytics can create inferential, or soft, measurements when direct sensors are unavailable, arrive too late, are expensive, or are unreliable. Research into fault diagnosis and predictive maintenance consistently shows that data quality, sensor coverage, feature relevance, and reliable context are essential prerequisites for useful prognostics [3]-[6]. In studies carried out in the oil industry, for example, random-forest methods have been used to detect faults in production lines and wells [7], predictive algorithms have been able to identify abnormal behaviour of electrical submersible pumps [8], and self-diagnostic methods have proved capable of assessing the confidence level in the outputs of multiphase flow meters [9]. These capabilities transform instrumentation from a simple role of observation into one of actively guaranteeing measurement quality.

Advanced process control (APC) represents the complementary aspect of decision-making. Although regulatory PID loops are still necessary, multivariable units with interacting constraints, long delays, nonlinearities, changing feed conditions, and economic trade-offs cannot be adequately handled by independent single-loop control. Model predictive control (MPC) and other APC techniques use dynamic process models to predict future behaviour, coordinate manipulated variables, and explicitly consider constraints. In gas compression, MPC has reduced variability and energy demand without sacrificing stable operation [13]. In offshore compression applications, zone-control MPC has also been shown to avoid undesirable operating areas and increase both stability limits and availability [14]. In oil-production networks, plantwide control, nonlinear MPC, economic MPC, and robust scenario-based approaches have been investigated to suppress slugs, allocate gas-lift, manage constraints, and optimise production [15]-[20]. These studies show why dependability and performance should not be treated as separate objectives: reducing oscillations, surge risk, slugging, valve erosion, pump overload, or excessive recycling can protect assets while continuing productive capacity.

The literature remains fragmented: papers on instrumentation mainly focus on detection performance or connectivity; those on maintenance focus on remaining useful life; and papers on control emphasise closed-loop performance or economic elements. Few studies address the engineering chain from measurement confidence through fault anticipation, constraint management, asset health, and plant-level outcomes. In Saudi Arabia, additional challenges comprise severe environmental conditions, the large number of brownfield sites, operational-technology cybersecurity, the availability of local skills, vendor interoperability, and model governance throughout the long lifecycles of the facilities. The reference model included in the 2025 Saudi oil and gas study illustrates how digital innovation can reduce costs and boost operating efficiency, while the other model is based on the literature and includes structured searching, thematic analysis, conceptual synthesis, and contextualisation.

This review intends to critically synthesise methods for utilising smart instrumentation and APC into a reliability-centred operating framework for oil and gas facilities in Saudi Arabia, in line with Vision 2030. The study is based on the following four objectives: first, to examine the evidence from 2020 to 2025 concerning smart sensors, IIoT, soft sensors, digital twins, fault diagnosis, predictive maintenance, and APC within the context of oil and gas operations; second, to explain the mechanisms by means of which the quality of measurement and control performance influences reliability, availability, energy intensity, throughput, and the amount of maintenance needed; third, to identify the factors that facilitate and those that hinder the implementation in Saudi Arabia; and fourth, to propose a staged architecture and a research programme that connects instrumentation assurance, predictive intelligence, control optimisation, asset management, and governance.

II. REVIEW METHODOLOGY

The study uses an integrative systematic review method, which is suitable for an engineering field covering instrumentation, control, reliability, maintenance, and digital transformation. The procedure follows a sequence of steps specifically, recognizing relevant literature, screening eligibility, thematic synthesis, and framework development—as described in the literature-based model, and restricts the evidence cited in the manuscript to papers published between 2020 and 2025. The searches were carried out using combinations of the following terms: oil and gas, petroleum, refinery, gas compression, gas lift, smart sensor, instrumentation, Industrial Internet of Things, soft sensor, fault detection, predictive maintenance, digital twin, advanced process control, model predictive control, economic MPC, reliability, process efficiency, and Saudi Arabia. The search was carried out using journals indexed in Scopus and Web of Science, as well as ScienceDirect, SpringerLink, Wiley, IEEE Xplore, ACS publications, and Google Scholar. For information on Vision 2030 and industrial digitalisation, we used only official Saudi sources.

To qualify, publications had to have been produced between January 2020 and December 2025, have a clear association with industrial measurement, process control, reliability, predictive maintenance, or the digitalisation of the oil and gas industry, and include sufficient technical detail to enable mechanism-based synthesis. Preference was given to peer-reviewed articles and high-quality conference papers. Any research which focused solely on consumer IoT, general business digitisation, or algorithms without a clear connection to an industrial process was excluded. Because the required citation period was 2020 to 2025, earlier foundational theory was not cited; instead, more recent studies applying or reviewing concepts such as MPC or reliability-centred maintenance were selected. The final evidence set included thirty core references, two of which were from Saudi institutional sources.

Data extraction was divided into five areas: measurement and sensing capability; data validation and diagnostic intelligence; predictive maintenance and digital-twin support; APC and optimisation; and conditions related to organisational or Saudi-context implementation. In every study, the synthesis considered the process asset, the variables measured or estimated, the analytical or control method, the reported reliability mechanism, the mechanism for operating efficiency, the implementation requirements, and the limitations regarding transferability. Rather than statistically combining the various performance percentages, the review uses a qualitative comparative synthesis because the evidence includes different assets, simulators, data sets, control objectives, and outcome definitions.

Credibility was achieved through source triangulation and careful interpretation. To identify general trends, the review articles were consulted [3]-[6],[28], while studies focused on oil and gas were used to examine field-specific mechanisms [7]-[20],[27]. To support the arguments about system integration, the research on digital twins, smart energy, and Industry 4.0 was referred to [11],[23]-[26]. The Saudi claims were checked by referring to a peer-reviewed study from Saudi Arabia [1], an official Vision 2030 report [30], and an earlier description of an Aramco facility [29]. Given this, the performance figures cited should be seen as applying only to individual cases and not as general standards. The resultant framework is conceptual and geared toward implementation; it does not provide causal validation for all Saudi facilities.

Table 1. Review protocol and analytical design.

Element	Review specification
Review design	Integrative systematic review with qualitative comparative synthesis and Saudi contextualization
Evidence window	January 2020-December 2025
Discovery sources	Scopus/WoS-indexed collections, ScienceDirect, SpringerLink, Wiley, IEEE Xplore, ACS, Google Scholar; dated official Saudi sources
Core search concepts	Oil and gas; instrumentation; IIoT; soft sensors; fault diagnosis; predictive maintenance; digital twin; APC; MPC; reliability; operational efficiency; Saudi Arabia
Inclusion	Peer-reviewed technical studies or authoritative dated Saudi sources with direct relevance to measurement, control, reliability, maintenance, or industrial digitalization
Exclusion	Pre-2020 publications; consumer IoT; generic digitization without industrial process relevance; unsupported promotional claims
Synthesis	Five themes: sensing, validation/diagnosis, prediction/digital twins, APC/optimization, implementation/governance
Final evidence set	30 core references, all dated 2020-2025

III. SMART INSTRUMENTATION AS THE RELIABILITY FOUNDATION

In a reliability-centered approach, the first issue to be dealt with is not optimization but whether the plant's present state is being measured correctly. It is possible for a transmitter to stay in operation even if its readings drift, for a flow meter to produce values which, although plausible, are biased, for an analyzer to suffer from sampling delay, and for the indication of a valve position to differ from the actual mechanical movement. These faults are dangerous since higher-level applications usually treat the measurements as valid. Smart instrumentation reduces this potential source of failure through incorporating device diagnostics, more detailed status codes, a record of calibrations, local processing, and communication health information alongside the main process variable. When combined with data from historians and asset-management systems, this information turns measurement uncertainty into an operational variable that can be monitored rather than something only found during maintenance.

The literature on predictive maintenance supports this idea. Systematic reviews have shown that predictive maintenance is effective only when it has synchronized condition data, sufficient history, meaningful features, scalable computing, and a feedback process that links predictions to maintenance decisions [4],[5]. Nordal and El-Thalji [6] go further by applying the concept to algorithms; they also apply it to a management structure that combines measurements, historical records, analytics, and maintenance operations. Such a systematic approach is especially important for facilities in Saudi Arabia since their instrument fleets may include equipment from various generations and using different protocols. If advanced analytics are introduced without first proving the naming conventions, timestamping, calibration stamps, handling of missing values, and the definition of sensor criticality, complex models end up learning about instrument defects rather than actual process behavior.

Various studies in the oil and gas industry have identified multiple practical smart-instrumentation methods. Barbariol et al. [9] created a machine-learning method for detecting anomalies in multiphase flow meters, which are devices that combine several sensing techniques in order to estimate the amounts of oil, water, and gas. A self-diagnosing meter can assign a level of confidence to a production measurement, allowing engineers or supervisory control systems to distinguish a real change in the reservoir or process from a reduction in the meter's accuracy. Lemos et al. [10] showed how an echo-state-network soft sensor can be used for monitoring and for fault detection in industrial processes, including actual oil and gas equipment. Soft sensors are of assistance in situations where data on laboratory composition, internal states, or measurements that are hard to obtain are not available at the frequency needed by control systems. Nevertheless, they should supplement, not replace, metrological practices: it is necessary to examine model residuals, prediction intervals, and fallback logic, and to carry out regular reconciliation with reliable measurements.

Machine-learning techniques are capable of turning sensor networks into useful information about equipment. M [7] applied random forests to the task of detecting and classifying faults in oil wells and in production or service lines, whereas Peng et al. [8] focused on the early detection of faults in electrical submersible pump systems. Mohammed [27] used actual equipment and process sensor data to predict failures of seawater pumps and found that temperature and pressure were influential factors. Alarms based on simple thresholds show that a variable has gone beyond a predefined limit; multivariate diagnostics detect abnormal relationships between variables; prognostic methods estimate the trajectories of deterioration; and prescriptive systems link the degradation state to particular operating or maintenance actions. Reliability increases as the system's design progresses from individual alarms to contextual diagnosis, on the condition that false positives, model drift, and sensor faults are explicitly taken into account.

Safety-related sensing can also involve the use of IIoT integration. Bany Salameh et al. [12] proposed a wireless sensor network that encompasses the entire process in order to provide an early warning of gas leaks, showing how distributed sensing, communication, and monitoring functions can be combined into one system. Although wireless instrumentation can reduce cabling costs and enhance coverage in hard-to-reach areas, its application in an industrial environment calls for consideration of battery life, radio propagation, redundancy, hazardous-area certification, latency, and cybersecurity.

Hu, together with his colleagues [11], suggested a reference architecture applying digital twins for monitoring and fault diagnosis of petrochemical processes, based on actual industrial sampling data. The advantage of the digital twin concept is that it retains context—specifically, the equipment topology, the relationships between processes, expected dynamic functioning, constraints, and state estimates—and can be combined with real measurements. The method's reliability derives from its ability to compare actual behavior with expected behavior, test hypotheses, predict when constraints will be reached, and support safer changes before implementation.

A key consequence is that information regarding the instrument's condition should be passed up the system. When a particular pressure transmitter is found to be drifting, the soft sensor has to be informed, the MPC estimator should lower its weight or switch to a validated alternative, the predictive-maintenance models must avoid treating the drift as a sign of equipment degradation, and the operators should be given a clear explanation for any change in control mode. This last aspect relates to the standard rules on data ownership, confidence states, the redundancy strategy, validation rules, and lifecycle maintenance.

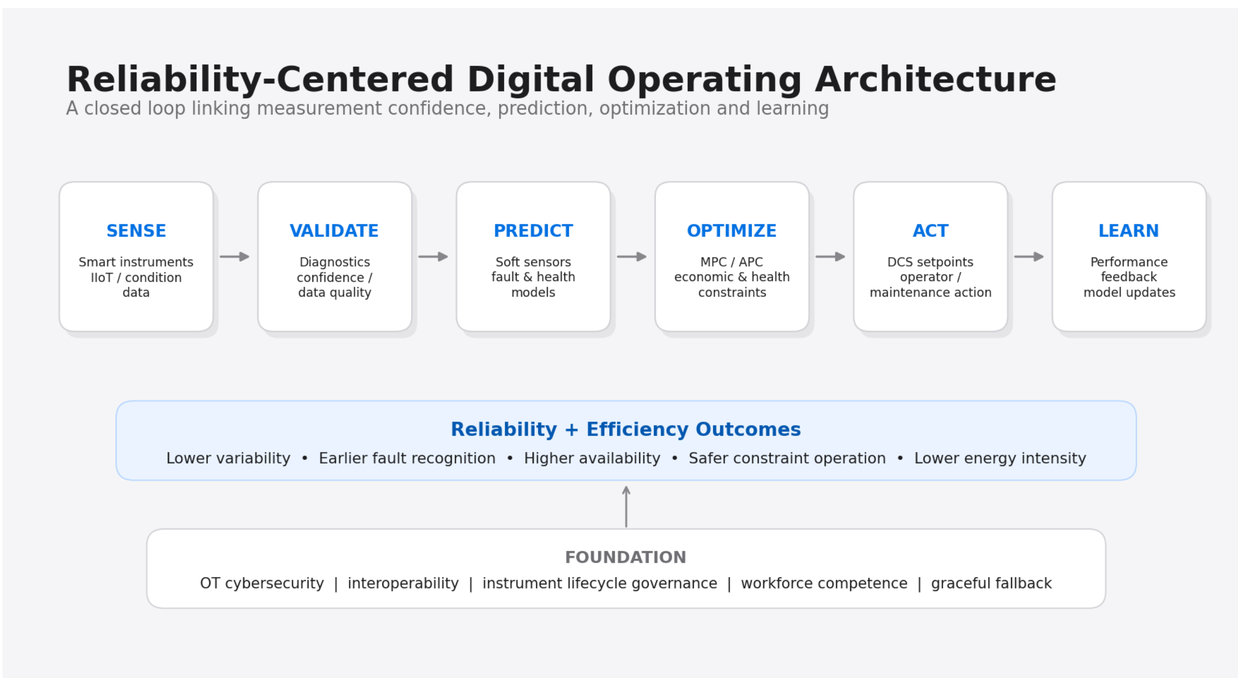

Figure 1. Integrated Sense-Validate-Predict-Optimize-Act-Learn architecture for reliability-centered digital operations.

IV. ADVANCED PROCESS CONTROL AND RELIABILITY-ORIENTED OPTIMIZATION

Once the quality of the measurement has been assured, APC can convert the information acquired into coordinated action. Traditional regulatory control is usually set up loop by loop, with each kind of controller—for instance, those controlling pressure, flow, temperature, level, speed, and composition—attempting to keep its own setpoint. For instance, the controller responsible for compressor suction pressure could increase the recycle flow while another loop changes the throughput; a well-control move may result in a change to the separator pressure or the gas capacity, and a refinery unit might sacrifice some of its energy efficiency in order to maintain product quality, since the constraints are dealt with indirectly. APC handles these interactions by forecasting the multivariable responses, making coordinated adjustments, and ensuring that the future paths stay within the prescribed limits. The more recent literature on APC still regards MPC as the main method used in the continuous-process industries where economic objectives, disturbances, and multivariable constraints interact [21],[22].

Gas compression is a particularly suitable example since reliability and energy efficiency are closely related. Giraldo et al. [13] applied Model Predictive Control with dead-time compensation to a gas-compression system and found that they were able to reduce both the variability and energy consumption while at the same time keeping the operation stable in the presence of disturbances. Gesser et al. [14] developed a zone-control MPC strategy along with the required supporting infrastructure for an offshore compression system, with the specific goal of avoiding undesirable operating regions and of increasing the stability margins and availability. These objectives directly match the requirements for Saudi gas-processing and oil-processing facilities: the suction and discharge pressures, the anti-surge margins, the compressor load sharing, the recycle flows, the temperatures, and the upstream disturbances all have to be co-ordinated without forcing the machines into damaging areas. Therefore, the use of an APC serves as a reliability measure when its constraints take into account the physical health boundaries of the equipment rather than just the production targets.

The same kind of coupling is seen in the oil production networks when looked at at the field level. Jahanshahi and others [15] investigated the plant-wide control of a gas-lifted oil production network, combining regulatory stabilization with optimization. Their study demonstrates that it is not possible to simply add optimization onto an unstable process; slugging, casing-heading, pressure oscillations, and separator interactions all require there to be a stable regulatory base in place first. Matias and his colleagues [16] further developed this idea by means of health-aware control, incorporating the degradation of choke valves into an MPC formulation so that production can be optimized while taking into account a health-critical erosion constraint. This involves an important conceptual change: asset health is now a controlled constraint rather than merely a maintenance report that is received after the operating decision has been made.

The nonlinearity and uncertainty of the behaviour also result in the development of more advanced methods. Soares et al. [17] designed a nonlinear model predictive controller for the stabilisation of a gas-lift oil well and used states that were deduced from sensor data to cope with variables which cannot be measured directly. Janatian and Sharma [18] dealt with uncertainty explicitly by means of a multi-stage scenario-based model predictive controller in order to optimise short-term oil production, thus showing the importance of robust feasibility when there are variations in reservoir or process parameters. Ribeiro et al. [19] proposed a simplified economic model predictive controller based on modifier adaptation with the aim of reaching an economic optimum while addressing model mismatch and the computational load. Adukwu et al. [20] applied a nonlinear model predictive controller together with control zones in order to suppress casing-heading instability in a mature gas-lifted system. Taken as a whole, these studies show a progression from simply holding setpoints to managing operating envelopes, uncertainty, health, and economics all at the same time.

The most practical method for dealing with APC when it comes to refining and gas processing is a hierarchical one. While the safety system must remain separate from economic optimisation, the limits and permissives defined by it set the firm boundaries within which the APC can operate. The APC then drives the unit towards a profitable or energy-efficient region without violating the various soft constraints such as compressor margin, furnace duty, column flooding tendency, product quality, emissions-related indicators, or equipment vibration limits. If a manipulated variable reaches its saturation point, the MPC should redistribute the control action amongst the other degrees of freedom rather than allowing a hidden loop conflict to occur.

The improvement in reliability is most clearly seen when the control performance is continuously monitored. An MPC system can deteriorate for a variety of reasons, for example because valves stick, instruments drift, there are changes in the composition of the feed, the models become outdated, the operators leave the controller in manual mode, or the constraints are set too conservatively. It follows that APC also needs to have a lifecycle management strategy, this involving the monitoring of the controller-service factor, the constraint residence time, the prediction error, the activity of the manipulated variables, the economic benefit, the frequency of bad measurements, and operator interventions. Thus, the same lifecycle loop which is required for smart instrumentation is completed.

Efficiency in operations also demands that objectives be selected carefully; a controller that is designed purely to maximize throughput might shift these costs onto energy use, flaring, equipment wear, or the need for maintenance. Although economic model predictive control provides a framework for including prices and penalties directly, it is just as important to incorporate terms that relate to health and sustainability. Recent research in the field of smart energy has shown that greater benefits can be achieved by combining AI, big data, IoT, and optimization in order to improve energy management [23]. The objective functions for oil and gas facilities in Saudi Arabia should therefore match the sites' priorities, which are to maintain stable export specifications, use the minimum amount of fuel gas, reduce recycling, achieve compressor efficiency, ensure a balanced use of steam and hydrogen, avoid flaring, comply with corrosion or erosion limits, and maintain throughput.

V. RELIABILITY: THE REVIEW IDENTIFIES FOUR MECHANISMS BY WHICH SMART INSTRUMENTATION AND APC TOGETHER IMPROVE RELIABILITY AND OPERATIONAL EFFICIENCY.

The first of these is the reduction of variability. As process variability consumes the operating margin, engineers are obliged to maintain the average conditions at a greater distance from safety, quality, or equipment limits. By improving the accuracy of the measurements, both noise and bias are eliminated and the MPC coordinates the various interacting variables while removing the disturbances. It is thus possible to work closer to an economically preferable constraint without increasing the risk [13-15]. Another method consists of the early detection of abnormal conditions. By means of smart devices, multivariate diagnostics, and soft sensors, deviations can be picked up before the usual high alarms are activated [7-10]. When the diagnostic results are incorporated into the control system, a gradual response can then be carried out, for instance by reducing the equipment load, changing the setpoint, redistributing the gas lift, increasing the frequency of monitoring, or setting a maintenance work order. This approach is an improvement on making a sudden transition from normal operation to a trip. Health-aware control demonstrates this principle by incorporating degradation directly into the optimization process [16]. Optimization process [16].

The third mechanism is constraint transparency. Even though oil and gas facilities have a large number of limits, not all of these are displayed explicitly in the operator interfaces or in the control logic. APC requires engineers to clearly specify the controllable variables, the manipulated variables, the constraints, the priorities, and the models. As a result of this engineering process, the bottlenecks become apparent. One can see, for example, that production is limited by compressor power rather than by reservoir capacity, by separator pressure rather than by well potential, or by analyzer uncertainty rather than by the actual product quality. Once the current constraint has been identified, more specific decisions regarding investment and maintenance can be made.

The fourth mechanism is concerned with coordinated decision-making concerning the asset's entire lifecycle. Predictive maintenance identifies when an asset may fail, and the APC then decides how the process should be carried out at that time. As a result, load-aware maintenance is obtained: the control layer can reduce the stress on a failing pump, valve, compressor or heat exchanger while production planning schedules the necessary repair. Almazrouei et al. [28] highlight both the potential and the data problems linked to the use of AI for predictive maintenance of oil-and-gas water-injection pumps. The key architectural idea is that prognosis should not end with a dashboard; it should influence operating envelopes, risk assessment, work prioritisation and planning, with human approval being required in instances where there are important safety or production implications.

Table 2. Technology-to-outcome pathways for Saudi oil and gas facilities.

Capability	Primary mechanism	Reliability KPI	Efficiency KPI	Key deployment risk
Smart instrument diagnostics	Detect drift, device degradation and bad-value states	Bad actor rate; calibration exceptions	Fewer manual checks; less troubleshooting time	Diagnostics not integrated into operating workflow
Soft sensors / data reconciliation	Estimate difficult variables and validate measurements	Residual trends; inferential confidence	Faster quality feedback; reduced analyzer delay	Model drift or use beyond validated envelope
Predictive maintenance analytics	Recognize degradation before functional failure	Lead time; false-alarm burden; avoided failures	Planned maintenance; reduced unplanned downtime	Biased labels, sparse failure data, false positives
MPC / APC	Coordinate variables and enforce future constraints	Constraint violations; instability events	Variability, energy intensity, throughput	Stale models, valve issues, low service factor
Health-aware optimization	Include degradation or health limits in control decisions	Remaining health margin; stress exposure	Productivity maintained within health envelope	Incorrect degradation model or poor governance
Digital twin integration	Reconcile plant state, test changes and support diagnosis	Model residual; diagnosis time	Reduced trial-and-error; faster optimization	Twin becomes visualization without lifecycle upkeep

VI. SAUDI VISION 2030 CONTEXT AND INTEGRATED ARCHITECTURE

The fact that Saudi Arabia has shown the kind of integration suggested in this review to be technically feasible is illustrated by Aramco's 2024 report on the Yanbu Refinery. This report describes a five-year digital transformation programme which included modernising the existing systems, extending the use of IIoT sensors, and making use of analytics and artificial intelligence. Because of one advanced AI application, the facility was able to increase its production capacity by 18 per cent, boost its profitability by 35 per cent, and reduce its Scope 1 and 2 greenhouse gas emissions by 14 per cent; however, since these figures apply only to that facility they cannot be generalised, yet they do indicate the extent of the benefits that can be achieved when data infrastructure and operational applications are implemented together [29]. The report also stresses the importance of training and of changing the company's culture, drawing attention to the need for operational discipline when introducing technology.

Aramco has likewise made public the information that the Khurais field makes use of hundreds of thousands of sensors distributed over more than 500 wells and uses an APC application for a conventional oil field, thus demonstrating the direct integration of field sensing, analytics, and optimisation. The main question at present is how to apply the experience acquired at the flagship facilities in order to establish a repeatable engineering standard for refineries, gas plants, stabilisation facilities, pipelines, terminals, water-injection systems, and smaller production assets.

Vision 2030 provides a favourable environment for enabling development; as the 2024 annual report states, investment within digital infrastructure, cloud technologies, artificial intelligence, and cybersecurity is considered essential if competitiveness is to be achieved and private-sector growth is to be promoted [30]. This strategy corresponds to four priority areas in the oil and gas sector. The first of these is localisation, which means that instrumentation diagnostics, APC model maintenance, industrial data engineering, and OT cybersecurity should become established local capabilities rather than being confined to one-off vendor projects. The second priority is energy and emissions efficiency, this involving reducing variability, optimising compression, improving furnace control, and detecting equipment faults early on in order to reduce the use of fuel and utilities without having to give up production. The third is resilient operations, which means ensuring a high level of availability for the energy and feedstock infrastructure in order to support the wider industrial diversification strategy.

The reason why brownfield interoperability is such a serious issue is that these facilities might be using legacy DCS systems, rely on proprietary device protocols, have serial networks, use different historians, and have inconsistent tag structures. Instead of carrying out a full replacement, it is more practical to adopt a step-by-step integration method—which involves the use of gateways, OPC UA, edge computing, standard information models, and criticality-based upgrades of sensors. OT cybersecurity must be included in this connectivity because the addition of more sensors and remote interfaces increases the attack surface, even though at the same time the control systems have to operate with high availability and deterministic behaviour. Consequently, network segmentation, identity management, secure remote access, patch governance, backup and recovery, configuration control, anomaly monitoring, and supplier security should be incorporated into the APC and instrumentation lifecycle and not left to a separate IT checklist.

The conditions in which equipment functions are also of importance. High ambient temperatures, dust, salinity in areas close to the sea, vibration, sour service, and hazardous environments are all capable of leading to a deterioration of sensing and communication systems. When instruments are being selected it is necessary to consider the possible failure modes of the whole measurement chain, including the impulse lines, the sample systems, the probes, the enclosures, the power supply, the communication links, and the environmental protection. Likewise, APC models must be able to cope with missing data and with a mismatch between the process model and actual conditions. As stated in the literature concerning gas compression, it is necessary to deal with delays and with missing real-time variables [13,14], while resilient oil-production optimisation demonstrates the value of explicitly taking uncertainty into account [18].

In the end, it is the way in which the system is governed that decides whether it can be sustainable. Every soft sensor, every anomaly model, and each MPC controller must have an owner, a validated schedule, a change-control procedure, a documented fallback procedure, and a performance metric. Operators should know the reasons behind the actions of the system rather than simply be informed that the system is 'AI enabled'. Engineers must have access to the model residuals and to the diagnostic evidence. The maintenance teams must be sure that the alarms reflect the real state of the equipment and not just the result of defective instruments. The fact that these requirements exist shows that the essential component of digital transformation should be a governed operating capability, not a software license.

Implementation Roadmap for Saudi Facilities

A false roadmap reduces both the technical and organisational risks. In the first phase, instrument assurance should be focused on; the facilities must assess the measurement loops in terms of their safety, control, reliability, and economic criticality, identify and address the chronic problems, set up a system of governance for calibration and diagnostics, improve the time synchronisation and the quality of the tags, and establish a baseline for control-loop performance. In the second phase, connected condition intelligence should be implemented; for important rotating equipment, valves, analyzers, areas susceptible to corrosion, and utility systems, further sensing should be added in cases where it fills a known gap in failure detection, and the edge and historian infrastructure should be made to standardise the contextual data.

In the third stage predictive diagnostics and soft sensing are incorporated. The models have to begin with clearly defined use cases, validated labels or expert rules, transparent performance criteria, and well-established operator procedures. The output from the models should include not only a degree of confidence but also reason codes. In stage four APC and dynamic optimisation are introduced. The units to be considered are those which show strong multivariable interactions, are operating continuously within constraints, have a high energy consumption, or involve costly variability examples are compressors, fractionation trains, gas-lift networks, furnaces and utility systems. The commissioning process should include model validation, a review of the constraints, training of the operators, a cybersecurity review and the setting of a baseline of the benefits.

In stage 5, reliability optimisation is carried out in a closed loop manner; the equipment-health indicators influence the allowable operating envelopes, the APC coordinates the available flexibility, maintenance planning is prioritised on the basis of condition, and digital twins are used to test changes. Human approval is still appropriate for major decisions. Progress from one stage to another must be based on the quality of the data, the stability of control, the level of readiness in the field of cybersecurity, the competence of the workforce, and proven business value rather than on a strict technological timetable.

These two rules apply in general. The first one is that graceful degradation must be ensured: should a sensor, a network link, the model, or the optimizer fail, the facility has to return in a predictable manner to validated regulatory control and to the standard operating procedures. The second one is that safety independence must be maintained: safety functions and the emergency shutdown protections should not depend on any optional optimization layers. Smart instrumentation and APC should be used to increase the margin available for safe operation, not to replace the protection system.

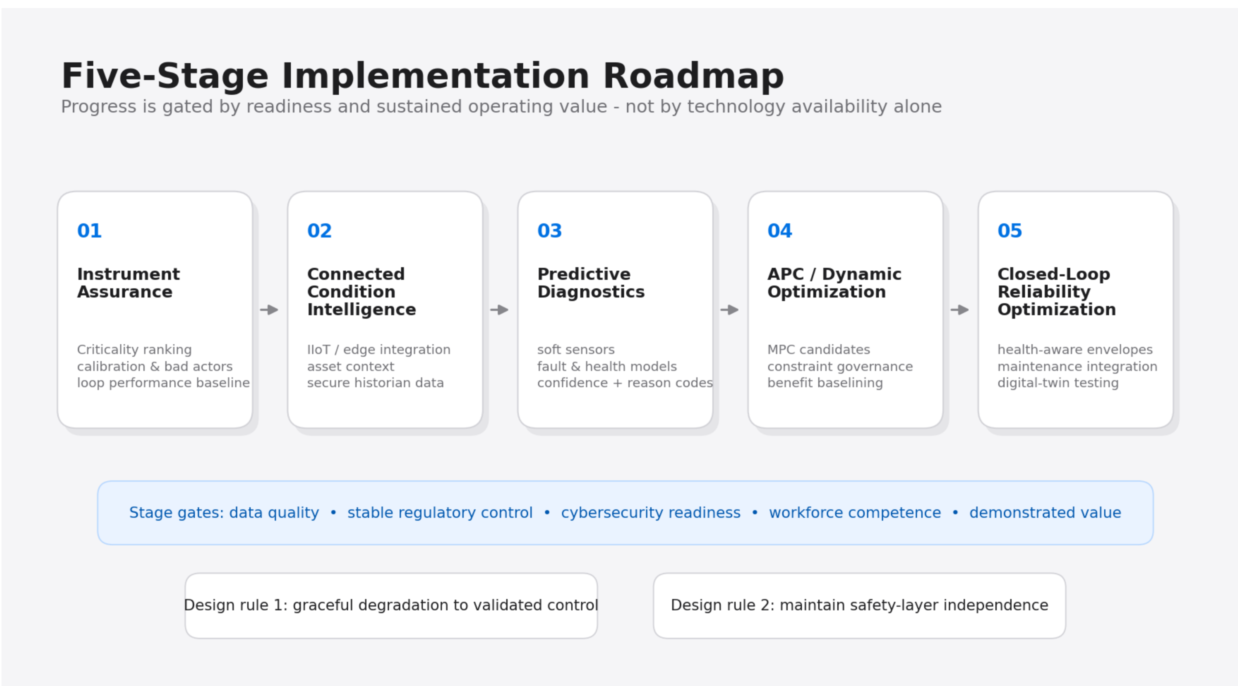

Figure 2. Five-stage implementation roadmap

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DOI: https://doi.org/10.64388/IREV10I3-1722785

VII. DISCUSSION, RESEARCH GAPS AND LIMITATIONS

The idea is that the greatest benefit is obtained when smart instrumentation and APC are designed as part of a single reliability loop; the way in which the system senses determines what it knows; the method it uses to validate determines what it trusts; the role of predictive analytics determines what it expects; the function of the APC determines how it responds; and maintenance governance decides if the capability stays efficient over time. A predictive model may be accurate but still have no practical relevance if no one alters a work order or an operating limit. An MPC controller might be mathematically optimal but can still be fragile if the main transmitters drift.

The evidence also warns against relying on the headline performance figures when preparing business cases. Although most APC studies do make use of specific units, models, disturbances, and constraints, predictive-maintenance studies require asset-specific data sets. It is therefore necessary to calculate the benefits taking into account each site's baseline variability, constraint losses, energy intensity, history of downtime, alarm burden, maintenance costs, and the number of controllable degrees of freedom. A more limited application that focuses on a well-defined constraint and has reliable data can generate greater sustainable value than a general AI platform which has no clear operating decisions.

Research in the future should focus on the design of control systems that are not merely tested in the field but also take into account the health aspects when operating in the tough conditions found in the Middle East. The main areas that require attention are uncertainty-aware soft sensors, the automatic incorporation of instrument-health data into MPC estimators, control strategies that take the degradation of equipment into account, the validation of digital twins under different crude or gas compositions, cyber-resilient fallback logic, and methods for measuring the reliability benefits resulting from reduced variability. It would also be useful to carry out comparative studies in the upstream operations, gas processing, and refining facilities in Saudi Arabia in order to tell the difference between general mechanisms and those that are specific to individual assets. The research should include not only a report on the accuracy of predictions or the economic aspects of the controller but also on the service factor, the number of false alarms, operator acceptance, the effort required for model maintenance, the energy impact, and the number of reliability events that have been avoided.

For the period spanning 2020 and 2025 it uses thirty core references, even though some fundamental work which is relevant but lies outside of that period is intentionally omitted. There is a greater amount of public case evidence available for some of the facilities that are digitally advanced than there is for the national asset base as a whole. It follows that the proposed architecture should be validated empirically by means of controlled pilots and on the basis of longitudinal operating data.

VIII. CONCLUSION

Smart instrumentation and APC should be seen as complementary elements of a comprehensive reliability-centred operating system for oil and gas facilities in Saudi Arabia. The use of smart sensors, self-diagnostics, soft sensing, IIoT, predictive analytics, and digital twins improves the quality and comprehension of plant data; meanwhile, MPC and the related advanced controls turn this information into coordinated actions, taking into consideration process, equipment, and fiscal constraints. The evidence examined shows that reliable methods exist for reducing variability, detecting faults earlier, preventing operation in hazardous areas, optimising energy use, and protecting productive capacity. Experience gained from digital transformation in Saudi Arabia indicates that these capabilities can be put into practice on a large industrial scale, and Vision 2030 offers strategic support for digital capability, efficiency, cybersecurity, and localisation.

Both the five-stage roadmap and the Sense-Validate-Predict-Optimize-Act-Learn framework stress the importance of having a solid foundation if autonomy is to be achieved. Instrument assurance, stable regulatory control, secure interoperability, model governance, operator competence, and the ability to make a graceful fallback are all essential prerequisites, not simply optional features. Facilities that assess their success in terms of sustained availability, energy intensity, constraint utilisation, maintenance effectiveness, and safe operation are more likely to attain lasting value than those which judge their digital progress by the number of connected devices or algorithms they have installed.

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