

Integrated Project Controls and Construction Supply Chain Technologies for Cost, Schedule and Risk Management in Saudi Giga-Projects

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Abstract: Saudi Arabia's giga-project programme brings together major capital investment, numerous interfaces, multiple contractors, imported materials, off-site production, and regulatory dependencies within compressed delivery periods. As a result, conventional project-control and construction supply-chain practices lose effectiveness when they operate as separate reporting activities. This article gives a critical examination of how integrated project control and construction supply-chain technologies can be used to enhance cost, schedule, and risk management in Saudi giga-projects. It uses a structured integrative review method to combine recent peer-reviewed research on earned value management, 4D/5D building information modelling, sensing-based progress monitoring, digital twins, artificial intelligence, blockchain, and digital supply-chain platforms with studies that are specific to Saudi conditions concerning delay, cost overruns, BIM adoption, and project governance. The synthesis indicates that technology generates value primarily when the data structures, control accounts, procurement packages, logistics milestones and risk registers are aligned with a common work breakdown and decision schedule. BIM and digital twins enhance the visibility of spatiotemporal information; sensing and analytics improve the verification and prediction of progress; blockchain can improve the traceability of transactions; and supply-chain visibility allows for earlier responses to interruptions in materials, fabrication and logistics. Yet, merely introducing technology in isolation can lead to the digital replication of fragmented processes. The review thus proposes an integrated control-to-supply chain framework that links baseline, actual, forecast and risk information across the owner, programme manager, contractor, supplier and logistics levels. The paper concludes that the success of Saudi giga-projects depends less on acquiring individual technologies and more on establishing interoperable data governance, following disciplined project-control procedures, obtaining reliable field evidence, and having contractual incentives to promote transparent information sharing between organisations.

Keywords: Saudi Giga-Projects, Integrated Project Controls, Construction Supply Chain, 5D BIM, Digital Twin, Cost Control, Schedule Control, Risk Management, Blockchain, Artificial Intelligence.

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1. INTRODUCTION

The pipeline of large and complex developments created by Saudi Arabia's Vision 2030

is very different in terms of its method of delivery from that of traditional standalone construction. Giga-projects combine urban development, transport, utilities, hospitality, industrialized

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construction, digital infrastructure, and public-realm assets. They frequently involve several delivery packages and have geographically scattered supply networks. Because of this scale there are a large number of technical and organizational interfaces, long-lead procurement risks, limitations on market capacity, and a close interdependence between design maturity, supplier performance, logistics, site productivity, commissioning, and cash flow. In Saudi Arabia, research still indicates that client-related delays, planning deficiencies, design changes, resource restrictions, and procurement-related risks are major causes of time and cost overruns (Alshihri *et al.*, 2022; Alenazi *et al.*, 2022). The issue therefore is not simply poor scheduling or inadequate purchasing, but the fragmentation of information and decision-making authority across project controls and the construction supply chain.

In the conventional project controls setup, performance is generally organised according to scope, work breakdown structures, cost accounts, schedules, earned value, change control and risk registers. Earned value management is still relevant since it involves a disciplined comparison of the planned value, the earned value and the actual cost, but forecast extensions can improve the estimates of the final duration and cost (Sackey *et al.*, 2020; Zahoor *et al.*, 2022). Yet standard control methods become less informative when progress data arrive late, procurement status is reported only through narrative comments, or supply-chain risks are separated from schedule logic. It is possible for a contractor to show acceptable physical progress even though the critical equipment is delayed in fabrication. On the other hand, materials can arrive early, leading to problems with inventory, handling and cash flow without at the same time improving the installed progress. Integrated control therefore requires visibility beyond the site boundary.

Digital construction research offers complementary capabilities. By linking schedule and cost data to the model elements, five-dimensional BIM enhances cost control and the visibility of changes (Abdel-Hamid & Abdelhaleem, 2023). Four-dimensional BIM and simulation can be used to detect time-space conflicts and improve the constructability of the schedule (Dashti *et al.*, 2021). ElQasaby *et al.*, (2022) review how sensing technologies, reality capture, and BIM comparison can automate the collection of progress evidence and reduce dependence on subjective reporting. In this regard, digital twins connect the digital replica of a physical asset with operational data in order to support simulation, prediction, and feedback (Opoku *et al.*, 2021; Hu *et al.*, 2022; Su *et al.*, 2023). These technologies are becoming increasingly important for giga-projects since the management issue is not

about storing more data but rather about detecting emerging deviations before they become irreversible.

In a similar way, research into construction supply chains shows a shift from transactional procurement to more connected information environments. Although the literature remains fragmented with regard to the applications of BIM, blockchain, the Internet of Things, and Industry 4.0 (Yevu *et al.*, 2021), digitalisation is capable of enhancing procurement transparency, coordination, traceability, and sustainability. Research on blockchain has concentrated on trusted data exchange, the traceability of payments, and linking tangible construction elements to smart contracts (Yang *et al.*, 2020; Lu *et al.*, 2021; Mahmudnia *et al.*, 2022). It has been suggested by researchers that BIM and blockchain should be integrated in order to create a reliable digital deliverable and a single source of truth beyond the limits of organisations (Hijazi *et al.*, 2021; Hijazi *et al.*, 2023). Furthermore, studies of supply-chain resilience identify capabilities that can reduce exposure to disruption, including visibility, flexibility, anticipation, resourcefulness, and digital connectivity (Ekanayake *et al.*, 2021; Osunsanmi *et al.*, 2021).

Integration is especially significant in Saudi Arabia. Studies of BIM adoption have identified advantages in coordination and quality, as well as obstacles relating to demand, expertise, awareness, standards, and organizational readiness (Al-Hammadi & Tian, 2020; Al-Yami & Sanni-Anibire, 2021; Alaboud & Alshahrani, 2023). The results indicate that digital tools should not be seen as simple add-ons. The control systems for giant projects must cover package baselines, supplier milestones, logistics constraints, contract administration, field production, and enterprise reporting. This review therefore concentrates on the interface between project controls and supply-chain technologies rather than assessing each area individually. Its main argument is that improvements in cost, schedule, and risk outcomes occur when the technology converts dispersed supply-chain events into timely control signals and the project-control system then turns these signals into accountable decisions.

2. AIM OF THE STUDY

The review provides a critical synthesis of peer-reviewed literature on integrated project controls and construction supply-chain technologies and presents an implementation-oriented framework for managing cost, schedule, and risk in Saudi giga-projects. Instead of viewing project controls as a reporting function, the review considers them to be a decision-making system. It evaluates the technologies according to their capacity to increase

data reliability, the quality of forecasts, cross-tier visibility, and the speed of intervention.

3. RESEARCH OBJECTIVES

The review is centred on five objectives. First, it identifies control problems arising from project scale, interface density, procurement complexity, and accelerated delivery in Saudi giga-projects. Second, it evaluates the role of EVM, 4D/5D BIM, sensing, digital twins, artificial intelligence, blockchain, and supply-chain platforms in managing cost, schedule, and risk. Third, it examines the mechanisms that connect project baselines with milestones across procurement, fabrication, logistics, installation, and commissioning. Fourth, it critically examines adoption barriers, including interoperability, data quality, governance, organizational capability, and contractual behaviour. Fifth, it proposes a practical integrated architecture and research agenda suited to the Saudi delivery context.

4. RESEARCH QUESTIONS

The review addresses four questions: the first of these, RQ1, investigates which failures in project control and the supply chain are most closely linked to a loss of visibility regarding cost, schedule, and risk in the delivery of giga-projects. RQ2 looks at how fragmented operational data can be turned into reliable control evidence and forecasts by means of digital construction and supply-chain technologies. RQ3 examines what governance, data, and contractual conditions are needed to achieve interoperability among owners, program managers, contractors, suppliers, and logistics providers. Finally, RQ4 aims to determine the most important research and implementation priorities in order to scale up integrated digital control from pilot applications to its use across the entire portfolio in Saudi Arabia.

5. REVIEW METHODOLOGY

Because the evidence base spans empirical construction-management studies, technology reviews, case studies, conceptual frameworks, and Saudi-specific adoption and performance research, a structured integrative review approach was used. The supplied Springer paper served only as a structural and academic-writing reference; no wording, evidence, tables, figures, arguments, or conceptual framework was reproduced. The review protocol therefore specifies the information sources, search strategy, eligibility criteria, quality-assessment dimensions, synthesis approach, and methodological limitations rather than relying on an unsystematic narrative review.

The search focused primarily on publications from 2020 to 2025, while a limited number of adjacent publications were retained when they were directly relevant to the Saudi context or to an established project-control method. Literature discovery used major scholarly databases and publisher platforms, including Scopus, Web of Science, ScienceDirect, SpringerLink, the ASCE Library, Emerald Insight, Taylor & Francis, Wiley, and MDPI. Bibliographic verification was performed against DOI records, official publisher pages, or authoritative institutional records. Search strings combined terms such as “project controls”, “earned value”, “cost control”, “schedule control”, “construction risk”, “4D BIM”, “5D BIM”, “digital twin”, “construction progress monitoring”, “artificial intelligence”, “construction supply chain”, “procurement digitalization”, “blockchain”, “supply-chain resilience”, “Saudi Arabia”, “Vision 2030”, “megaproject”, and “giga-project”. Boolean combinations required technology-focused records to address construction management, delivery, procurement, or project performance. Eligible sources were peer-reviewed journal articles that provided a clear method, empirical evidence, a substantive conceptual contribution, or a structured review relevant to at least one of four analytical areas: integrated project control, digital progress and forecasting, construction supply-chain digitalisation, and Saudi construction performance or technology adoption. Vendor material, promotional commentary, non-peer-reviewed opinion, unverifiable records, and studies unrelated to construction delivery were excluded. Peer-reviewed conference papers were excluded from the final evidence set to maintain a consistent journal-article basis; peer-reviewed review articles were eligible where they addressed technology maturity, evidence synthesis, or research gaps. Because this was a structured integrative review rather than a registered systematic review supported by a preserved deduplication database, no unverified PRISMA counts or screening totals are reported.

Quality assessment was qualitative and comparative. Each candidate source was examined for peer-review status, clarity of research design, relevance to cost, schedule, risk, or supply-chain control, transparency of data or cases, evidence of validation, and transferability to complex project environments. For digital technologies, the review distinguished operationally demonstrated applications from conceptual proposals. Saudi-focused studies were assessed for contextual relevance to governance, adoption, delay, cost, and coordination conditions. The DOI and bibliographic details of all 30 references were cross-checked against official publisher pages, DOI records, or authoritative scholarly records. The synthesis used

thematic coding to compare evidence on control integration, digital visibility, supply-chain coordination, predictive decision support, and implementation barriers. Because study designs and outcome measures were heterogeneous, meta-analysis was not appropriate; conclusions are therefore interpretive and mechanism-focused rather than pooled statistical estimates.

6. THEMATIC LITERATURE REVIEW AND CRITICAL ANALYSIS

6.1 From Periodic Project Controls to Integrated Decision Control

The literature indicates a distinction between measurement and regulation. While EVM can display variations in both cost and schedule, its managerial usefulness is determined by the quality and timeliness of the evidence relating to progress. Sackey *et al.*, (2020) point out the importance of time-sensitive measures when it comes to forecasting duration rather than using cost proxies, and Zahoor *et al.*, (2022) show the pragmatic advantages of having an organized approach to control and forecast assessment in building projects. However, in the case of a giga-project, control accounts include design release, procurement, manufacture, shipment, customs, site receipt, installation, testing and handover. Unless milestones are included in the integrated master schedule or are linked to cost accounts, conventional indices can be used to describe past performance without revealing the mechanism that will cause the next variance. Sander *et al.*, (2022) develop the idea of integration by means of a digital project twin which combines cost, schedule, and quantitative risk analysis; what is important here is not the term 'twin' itself but rather the clear connection between uncertainty and the cost and schedule aspects. This is especially the case with respect to Saudi giga-projects, since a delay in one high-value imported package can have a cascading effect on the enabling works, the access sequencing, the temporary facilities, the specialist labour, the commissioning, and the revenue readiness. Project controls should therefore treat risk as a dynamic exposure associated with activities, cost accounts, procurement packages and interfaces, rather than as a separate record which is periodically reviewed.

6.2 BIM, Sensing, and Digital Twins as Control Evidence

BIM acts as a means of control when model elements are linked to measurable aspects of scope, schedule activities, quantities, and cost. The research carried out by Abdel-Hamid and Abdelhaleem (2023) and Razak *et al.*, (2022) illustrate how 5D BIM can assist with cost control through integrating schedule and cost data. Dashti *et al.*, (2021) go further by applying 4D BIM to the automated management of

time-space conflicts through the use of simulation; they show how schedule logic can be checked against positional constraints before conflicts appear on site. The ability provided by these features is useful in giga-project zones where contractors might bid for access, cranes, laydown areas, roads, or work fronts. A major issue concerning project controls is the reliability of reported actual progress. ElQasaby *et al.*, (2022) look at the combination of BIM with sensing technologies as a means of monitoring construction progress and show the potential of reality capture when comparing as-built models with planned ones. With regard to integrated controls, this implies that evidence from the site can be used to update the quantities and the installation status, thus avoiding reliance on subjective assessments of the percentage of work completed. However, the fact that data is collected automatically does not guarantee that earned value will be reliable. It is necessary to define the level of detail of the model, the coding of objects, the coordination with the WBS, the acceptance criteria, and the data latency so that each detected object can be linked to the contractual and control milestones. Otherwise, even sophisticated sensing may produce accurate data which cannot be brought into line with the payment or schedule logic. Research has extended the digital-twin concept beyond periodic model comparison toward continuous information exchange, simulation, and feedback. The studies by Opoku *et al.*, (2021), Madubuike *et al.*, (2022), Hu *et al.*, (2022), Khallaf *et al.*, (2022) and Su *et al.*, (2023) collectively indicate substantial potential, but also uneven maturity and inconsistent lifecycle integration. Likewise, Salem and Dragomir (2022) stress a step-by-step development process moving from BIM through to monitoring and then to more autonomous control. Therefore, the most practical near-term application for giga-projects is not a complete "city twin" but a federated project-control twin which brings together key package status, production rates, schedule logic, cost exposure and risk scenarios. This more limited definition is feasible and makes certain that the technology stays linked to decision-making.

6.3 Supply-Chain Digitalization and Traceability

The supply chains in the construction industry are fragmented, which limits real-time visibility (Tezel *et al.*, 2020). Yevu *et al.*, (2021) point out that research into digital supply chains and procurement includes topics such as BIM integration, Industry 4.0, blockchain, and sustainability, but this research is still fragmented among separate research streams. This state of fragmentation is also evident in practice, since procurement systems may have purchase orders, suppliers may hold the fabrication data, freight forwarders keep track of the shipment milestones, and the project-controls teams update the schedules manually. The central integration

challenge is to create consistent event definitions and data relationships, not merely to connect additional software. The research on blockchain focuses on trust, immutability, and cross-organizational transactions. Yang *et al.*, (2020) show how public and private blockchains can be used in construction business processes. Sheng *et al.*, (2020) look at quality information management. Lu *et al.*, (2021) linked smart construction devices to blockchain oracles, demonstrating the way in which physical events can generate trusted digital records. Mahmudnia *et al.*, (2022) examine the applications, advantages, and limitations, covering intelligent contracts and information transparency. Hijazi *et al.*, (2021, 2023) look at the combination of BIM with blockchain for the reliable delivery of construction supply-chain data and for establishing a single source of truth. The important point is not that all giga-projects need to use blockchain, but that high-risk transactions between organizations require verifiable histories of events and clear ownership of the data. Although conventional databases are able to carry out many of these functions provided that there is strong governance, blockchain provides value when the demand for distributed trust and tamper resistance makes the extra complexity worthwhile.

6.4 Resilience, Predictive Analytics, and Early Warning

The literature on supply-chain resilience shifts the emphasis from efficiency to anticipation plus response. Ekanayake *et al.*, (2021) point out capabilities including visibility, flexibility, adaptability, resourcefulness, and anticipation in the case of supply chains in the industrialised construction sector. It is claimed that construction 4.0 technologies can boost resilience by increasing visibility when disruptions occur (Osunsanmi *et al.*, 2021). Since these conclusions are directly applicable to giga-projects which depend on off-site manufacturing and global logistics, a resilient control system should keep a close eye on leading indicators such as design-release readiness, the ageing of vendor drawings, progress in manufacturing, inspection hold points, logistics bookings, customs documentation, delivery reliability, buffer consumption and preparation for alternative sources.

Artificial intelligence can boost predictive capabilities when combined with these leading indicators. Egwim *et al.*, (2021) describe ensemble techniques used for predicting construction delays, demonstrating machine learning's ability to identify nonlinear combinations of risk factors. However, even if predictive performance is achieved, there is still a need for causal interpretation. In Saudi projects, scope and delivery strategies frequently change and the contractors vary, which means that models developed from data on past projects may fail

to perform well when the way in which projects are operated changes. The most defensible solution is human-in-the-loop analytics, in which machine learning identifies emerging exposures and planners, cost engineers, procurement specialists, and risk managers then interpret the causal relationships and decide on appropriate interventions.

6.5 Saudi Adoption Conditions and the Integration Gap

Studies carried out by Saudi BIM experts show that the institutional and organizational capabilities have an impact on the adoption of technology. Al-Hammadi and Tian (2020) pointed out the main barriers to the use of BIM, these being a lack of demand, expertise, and awareness. Al-Yami and Sanni-Anibire (2021) also mention policy and execution constraints, although they stress the coordination advantages. Alaboud and Alshahrani (2023) have examined the relationships between the different factors influencing adoption and point out the importance of awareness and leadership. Alghamdi *et al.*, (2022) look at BIM and sustainable design in the Gulf region and confirm the role of organizational and community factors. These studies warn against assuming that digital integration can be taken for granted when it comes to giga-projects.

Saudi performance studies also make it clear why integration is important. Alshihri *et al.*, (2022) point out the risk factors associated with time and cost overruns, while Alenazi *et al.*, (2022) demonstrate the impact of delays caused by the client. Together, these conclusions indicate that controls should take into account decision latency and the interfaces on the owner's side, and not simply the productivity of the contractor. A supply-chain platform cannot compensate for late approvals; if the design packages are not mature, a complicated schedule cannot ward off delays in procurement. It is therefore necessary for the integrated architecture to treat governance events such as design acceptance, technical submittal approval, change authorization, commercial instruction, and interface release as measurable milestones with clearly assigned owners.

Table 1 gives an overview of the technologies according to the control problems they address. The comparison shows that no one technology satisfies all control requirements. EVM provides disciplined performance measurement but has limited physical verification. BIM offers a clearly defined scope and multi-dimensional visualization yet relies on the quality of the coding. Sensing strengthens the evidence of actual progress, but this evidence has to be interpreted. Digital twins support simulation and prediction but demand mature integration. Blockchain provides traceability but does not overcome poor process design. AI is capable of

detecting patterns, but it is susceptible to data drift and suffers from explainability problems. The

managerial issue in this case is therefore orchestration.

Table 1: Comparative contribution of digital and control technologies to integrated giga-project management

Technology	Primary control contribution	Strongest value	Key dependency	Principal limitation
EVM / schedule analytics	Variance and forecast discipline	Cost/schedule performance visibility	Reliable baseline and progress rules	Weak supply-chain causality if milestones are omitted
4D/5D BIM	Scope-time-cost integration	Change, constructability and spatial sequencing	Consistent WBS/CBS/object coding	Model detail can exceed control usefulness
Sensing / reality capture	Objective actual-progress evidence	Reduced subjective percent complete	Acceptance logic and model alignment	Detection is not equivalent to earned acceptance
Digital twin	Dynamic simulation and feedback	Scenario testing and forward visibility	Real-time integration and validated models	High integration and governance burden
Blockchain	Traceability and distributed trust	Auditable cross-party transactions	Clear data ownership and oracle design	Complexity without value in low-trust-neutral cases
AI / ML	Predictive early warning	Pattern detection across many variables	Representative data and human review	Data drift, opacity and false confidence
Digital supply-chain platform	Supplier/logistics visibility	Earlier intervention on long-lead packages	Structured milestones and supplier participation	Can digitize fragmented processes without integration

The argument is shown in an integrated control-to-supply-chain loop in Fig. 1, comprising procurement and supplier milestones that are linked to the baseline scope, cost, schedule, and risk; the digital recording of field and supply-chain events; validated actuals being used to update performance

and forecasts; analytics being applied to test scenarios; and governance forums approving corrective actions. The cycle is deliberately circular since each intervention changes the future baseline assumptions, the level of risk exposure, or the supply-chain priorities.

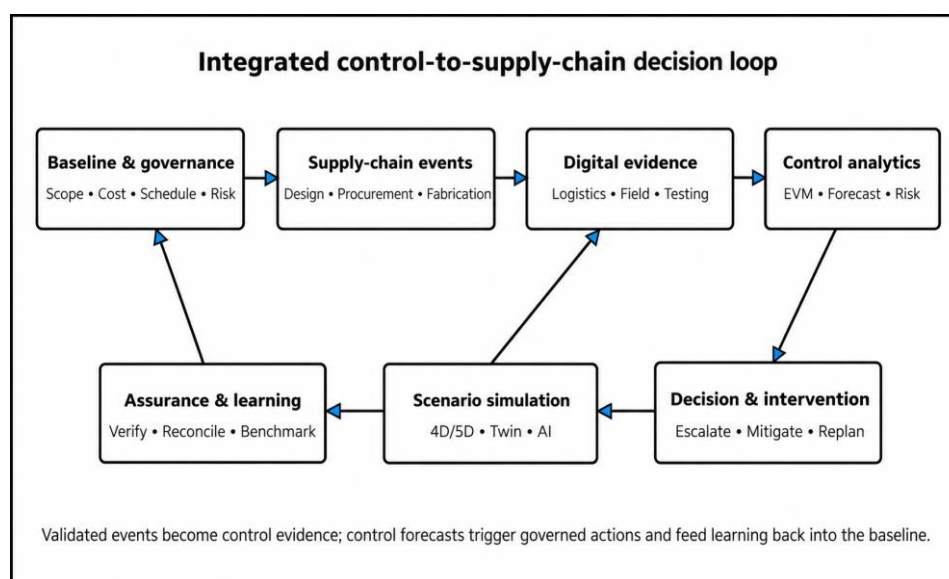


Figure 1: Integrated control-to-supply-chain decision loop for cost, schedule, and risk management.

6.6 Integration Architecture for Saudi Giga-Projects

An effective architecture must begin with standard coding. At the appropriate level of decision-making, the WBS, cost breakdown structure (CBS), organisational breakdown structure, location breakdown structure, procurement package identifiers, model objects, supplier deliverables, and risk identifiers should all be cross-mapped. If this semantic backbone is not established, integration will consist of a series of point-to-point interfaces. The next step is event capture: this involves recording design status, purchase orders, vendor documents, factory progress, inspection, shipment, customs clearance, site receipt, installation, test completion, and the quantities that are accepted. Each event must have a definition, an owner, a timestamp, an evidence source, and a link to the schedule and cost.

The control layer converts events into measures. By using EVM and schedule analytics you can analyse variance; 4D/5D BIM allows you to visualise the locations where variance is occurring; sensing enables you to verify the actual work being carried out; risk models allow you to quantify exposure; and AI helps in detecting trends that

require attention. The decision layer is just as crucial. It should set off alerts when there is a deterioration in forecasts, an increase in supplier slippage or a rise in interface risk. Corrective actions have to be associated with the responsible parties and the expected consequences for cost, schedule and risk. This stops dashboards from becoming a passive reporting surface.

Table 2 presents a governance matrix for the proposed architecture, with the owners and programme managers establishing the data standards and control thresholds. The contractors are responsible for updating the integrated schedules and package plans, suppliers provide the structured fabrication evidence, and the logistics providers keep up the movement and customs milestones. Independent assurance will verify the critical data and the forecast assumptions. The contractual mechanisms must specify the data timeliness, coding, evidence, auditability and the procedures to be followed in the case of non-compliance. These requirements are most important when multiple tier-one contractors are using different enterprise systems.

Table 2: Governance matrix for integrated project-control and construction supply-chain data

Actor	Required control responsibility	Digital evidence	Governance focus
Owner / programme manager	Common coding, thresholds, change and interface governance	Approved baseline, decisions, enterprise risk	Cross-package consistency and escalation
Tier-one contractor	Integrated schedule, cost forecast, package and field control	Progress, productivity, procurement and change records	Forecast integrity and corrective action
Supplier / fabricator	Milestone and quality status for long-lead items	Vendor documents, fabrication, inspection evidence	Early warning and recovery commitment
Logistics provider	Transport, customs and delivery milestone updates	Booking, tracking, border and receipt records	Route, buffer and delivery reliability
Independent assurance	Risk-based verification and reconciliation	Sampled source evidence and forecast challenge	Data lineage, auditability and bias control

Figure 2 shows the implementation process as a course of maturity, rather than as an immediate shift in technology. In stage 1, control discipline and common coding are introduced; in stage 2, procurement and supplier milestones are combined; in stage 3, the automation of evidence of progress and risk alerts takes place; in stage 4, predictive analytics and scenario simulation are introduced; and in stage

5, the package-level controls are federated into programme and portfolio decision support. This is similar to what has been observed in the literature on Saudi Arabia's use of such tools: advanced tools are unlikely to generate lasting value if awareness, capability, standards and process ownership remain weak.

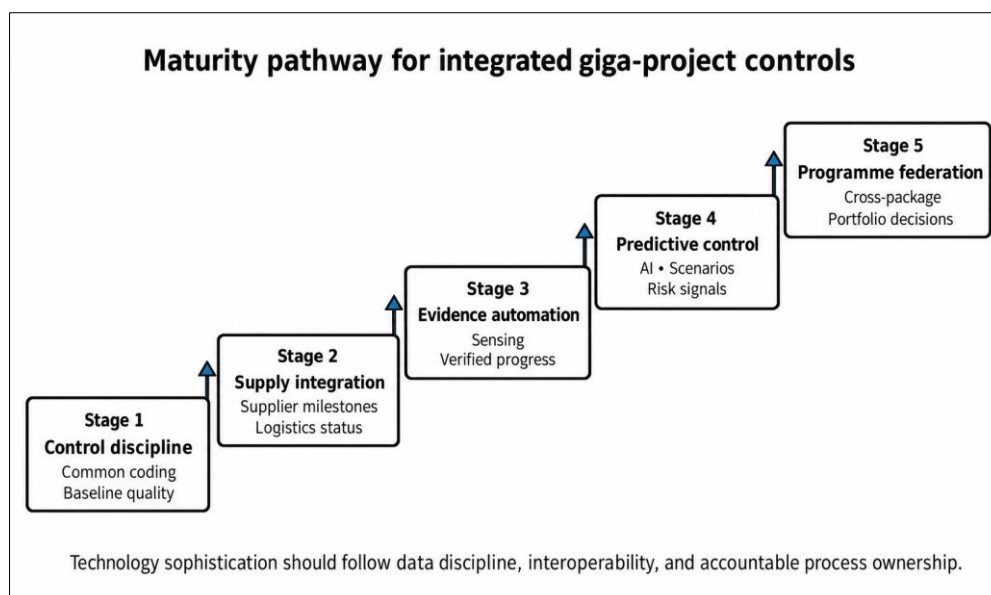


Figure 2: Phased maturity pathway from control discipline to portfolio-level predictive integration

6.7 Control Performance Metrics for Integrated Delivery

Integrated architectures also need metrics that reward anticipation rather than relying on explanations after the fact. Since traditional variance indices are useful for imposing a standard approach to performance, they should be kept, but they should be supplemented by supply-chain and decision metrics. Examples of such metrics are forecast stability, the percentage of critical packages having verified supplier evidence, the average approval ageing, milestone reliability, the time taken to close logistics exceptions, the risk-response lead time, and the percentage of forecast variance that can be accounted for by identified causal events. These metrics allow one to tell the difference between a project that reports accurately and one that intervenes early; they also show up data-quality problems, such as frequent manual changes, unexplained changes in status, or large differences between what suppliers claim and what has been verified as actual progress, all of which point to poor control integrity. Similar definitions at the programme level enable benchmarking between contractors who do not use the same software. The idea is to standardise the meaning while at the same time allowing different systems to generate compliant data. Assurance teams can then select high-risk transactions and trace each reported status back to the source evidence, the approval history, and the forecast consequences. This produces a defensible audit trail and allows learning to take place among different packages. Over time, aggregated metrics can highlight recurring bottlenecks in design approval, procurement, logistics, or commissioning and help owners to modify their governance arrangements, framework agreements, or market-capacity strategies before the

same failure pattern impacts later phases of the programme, thus setting up accountable cross-project learning cycles.

7. DISCUSSION

What the synthesis indicates is that the main innovation does not lie in any particular technology, but rather in combining control logic with supply-chain event logic. Instead of asking the traditional project controls question — "Are we ahead or behind schedule?" — supply-chain management asks "Will the resources and materials be available when required?" Therefore, giga-project governance has to take account of both questions simultaneously. A schedule forecast which ignores fabrication and logistics is structurally incomplete, and a procurement dashboard that fails to quantify the downstream effects on schedule and cost offers only weak prioritization.

Digital technologies may help to close this gap, but they also bring about new kinds of failures. Problems with interoperability can result in there being competing "single sources of truth". If the installation quality is not accepted, automated progress figures may overstate the earned value. Bad data can be permanently recorded by means of blockchain. AI is capable of producing convincing risk scores even when the data is biased or unstable. Where reliable feedback is absent, digital twins may amount to little more than visualisations. Therefore assurance must change as a result of digitalisation. The control environment now includes provisions for data lineage, role-based approvals, reconciliation rules, model versioning and forecast challenge sessions.

There is likewise a strategic aspect concerning the assimilation of Saudi giga-projects involving the workforce. The quick growth of programs leads to an uneven level of maturity among the project owners, consultants, contractors, and suppliers. If a platform is requested without at the same time having capabilities in building planning, cost engineering, procurement, risk management, data management, and model coordination, fragmentation may be transferred to the digital level. A more effective method is to combine the establishment of minimum data standards, the development of competency specific to each role, and phased assurance. This is in line with the Saudi BIM adoption studies which look at expertise, awareness, leadership, and institutional support, not simply the availability of software (Al-Hammadi & Tian, 2020; Alaboud & Alshahrani, 2023).

8. RESEARCH GAPS AND FUTURE RESEARCH

Several important research gaps remain. Firstly, the empirical evidence concerning integrated project-control and supply-chain structures is less advanced than that available on individual technologies. Future research needs to look into whether integrated procurement, logistics, earned value, and risk signals have a significant effect on forecast accuracy or on intervention lead time. Second, research in Saudi Arabia should go beyond surveys relating to adoption and instead use longitudinal project data from giga-project packages, with the inclusion of anonymised benchmarking carried out under commercial confidentiality. Third, interoperability should be subjected to further investigation. Research ought to look into the practical ways in which WBS, BIM objects, cost codes, procurement packages, digital product passports and risk taxonomies can be mapped to one another and examine how these mappings cope with change. Fourth, predictive systems need to be externally validated across several project types, contractors, and phases. Data drift, concept drift, missing data, as well as strategic reporting behaviour should be treated as control risks rather than merely as technical issues. Fifth, research should compare centralised common-data-environment architectures with distributed ones such as blockchain in order to establish when the extra complexity yields tangible gains in terms of trust or transactions.

In the end, implementation research ought to examine the role of commercial incentives. Although technology may make sharing feasible, organisations might still be unwilling to share transparent supply-chain data since it can expose supplier delays, design immaturity, approval bottlenecks, and disruption caused by the owner. Contract models, data rights, liability issues, and incentive arrangements should be looked at with the same level of intensity as analytics;

integrated controls will continue to be institutionally weak even if technically feasible provided that information disclosure and commercial behaviour are not brought into line.

9. PRACTICAL, MANAGERIAL, AND POLICY IMPLICATIONS

In practice, giga-project teams must set up an integrated control data dictionary before introducing dashboards; for each important procurement and logistics milestone they should identify the activities involved, the cost exposure, who is responsible for the risks and the evidence requirements. Managers should concentrate on leading indicators and on reviews that are based on exceptions rather than on more reporting. The weekly control forums should separate out the observed facts, the forecast assumptions, the quantified exposure and the authorised actions.

In terms of the programmes involved, owners should require that the coding be interoperable, that supplier data be provided in a timely and structured manner, and that there be auditable evidence of progress under each contract. The digital requirements must be proportionate to the criticality of the package in order that small suppliers should not be excluded because of excessive complexity. Policy-makers and client organisations can help to promote market development by establishing common guidance on BIM and data exchange, by creating competency frameworks and by setting out reusable information requirements. Research has shown that demand signals and institutional leadership are important factors in promoting the adoption of BIM in Saudi Arabia (Al-Yami & Sanni-Anibire, 2021; Alaboud & Alshahrani, 2023). When clients have consistent requirements, this leads to a reduction in the need for duplicated configurations and improves comparability between programmes, a benefit that also extends to integrated controls.

10. LIMITATIONS

The review has certain limitations, such as the variety of methods, terminology, and the different stages of development among the studies chosen. Since a large number of the studies concerning digital twins, blockchain, and AI are merely conceptual or based on specific cases, the advantages of these technologies cannot be regarded as assured outcomes for any project. There is relatively little peer-reviewed evidence available on giga-project control architectures in Saudi Arabia, which means that the findings from other construction situations have to be applied with care. Furthermore, a meta-analysis has not been carried out because consistent reports of comparable quantitative effect sizes are not available. It is therefore appropriate to regard the

architecture proposed here as a testable integration model rather than as a confirmed causal solution.

11. CONCLUSION

Saudi giga-projects are increasing the interdependence between project controls and construction supply chains. If baseline control information does not go beyond the site boundary or if the data on procurement and logistics are not combined with forecast logic, cost, schedule, and risk performance cannot be managed effectively. As the evidence examined indicates, EVM, 4D/5D BIM, sensing, digital twins, blockchain, AI and supply-chain platforms all address part of the problem, but their value relies on disciplined integration.

The most believable approach consists of using a common control framework with identical identifiers and the same rules regarding scope, cost, schedule, procurement, logistics, physical progress and risk. By means of digital capture, events from suppliers and the field are turned into verified actual figures; forecasting and simulation then convert these actual figures into forward-looking exposure; and it is through governance that exposure leads to timely corrective action. It is this structure which shows why digital maturity has to be developed in a sequential manner: common coding and control discipline must come before automation, and predictive analytics must follow on from reliable data integration rather than replace it. For Saudi owners and project managers the important managerial point is to treat data as part of project control—that is, as contractual, auditable, proportionate and decision-related information. The researchers' primary concern is to test integrated architectures by using longitudinal data from Saudi projects and to measure forecast accuracy, response time, control reliability, and the influence of commercial behaviour. The future of control over giga-projects will not be a larger dashboard; rather it will be an interoperable decision system which connects what was planned, what has happened, what is moving through the supply chain, what is likely to happen next, and who is responsible for altering the outcome

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