CONSTRUCTION MANAGEMENT

An Integrated Digital Project Controls and Risk Management Framework for Reducing Delay in Major Infrastructure Projects: A Construction Management Approach for Saudi Arabia

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Published October 2026

Abstract

Background: Major infrastructure projects involve complex interactions between design, procurement, construction, resources, interfaces, approvals, safety, logistics and external stakeholders. Delays can arise when project-control systems, risk management and digital information systems operate independently rather than as an integrated decision-support system.

Purpose: This study proposes an Integrated Digital Project Controls and Risk Management Framework (IDPCRF) for identifying, predicting, monitoring and mitigating delay risks in major infrastructure projects in Saudi Arabia.

Methodology: The research develops a conceptual framework through structured review of project-control, risk-management and digital-construction principles. The proposed framework integrates schedule control, cost control, risk registers, change management, document control, progress measurement, interface management, field data, dashboards and early-warning mechanisms. A conceptual delay-risk model is developed to connect risk probability, impact, response status and schedule exposure.

Proposed framework: The framework consists of six interconnected functions: (1) planning and baseline control; (2) progress measurement; (3) risk and opportunity management; (4) change and interface control; (5) digital information integration; and (6) predictive early-warning and management action.

Findings: The proposed framework provides a structured pathway from data collection → risk identification → risk quantification → early warning → management intervention → impact measurement → lessons learned. It proposes a Digital Delay Risk Index (DDRI) as a potential decision-support metric. The numerical examples presented in this paper are illustrative and are not empirical findings.

Originality: The principal contribution is the integration of project controls, risk management and digital information into one delay-reduction framework rather than treating schedule, cost, risk and field information as separate management functions.

Conclusion: Effective delay management should move from reactive reporting toward proactive identification and intervention. The proposed framework provides a foundation for empirical validation using real infrastructure-project data.

Keywords: project controls; construction delay; risk management; digital construction; schedule management; infrastructure; early warning; project management; Saudi Arabia; construction analytics; Primavera P6; dashboard; delay reduction

1 Introduction

Large infrastructure projects are characterized by multiple stakeholders, complex interfaces, extensive engineering documentation, numerous work packages and long execution periods.

Project performance is commonly measured through:

- cost;
- schedule;
- scope;
- quality;
- safety; and
- resource performance.

However, delays frequently arise through interactions between these variables. For example:

Design change → delayed approval → delayed procurement → delayed material delivery → delayed construction → resource disruption → productivity loss → schedule impact.

Similarly: Incomplete information → field uncertainty → work interruption → rework → additional cost → schedule delay.

Consequently, delay management cannot be treated solely as a scheduling problem. It is a combined project controls, risk, information, change and interface management problem.

1.1 Research problem

Traditional project reporting often identifies problems after they have already affected the schedule.

A typical reporting cycle may be:

Problem occurs → Progress declines → Monthly report identifies delay → Management investigates → Corrective action.

By that point, recovery may be difficult.

The proposed research changes the sequence to:

Risk signal → Early warning → Risk assessment → Management intervention → Monitoring → Outcome measurement.

This represents a transition from reactive control to predictive project management.

1.2 Research gap

Existing project-management approaches provide established methods for:

- scheduling;
- risk management;
- cost control;
- change management;
- earned-value analysis;
- document control.

Digital construction technologies additionally provide opportunities to integrate:

- BIM;
- cloud collaboration;
- mobile field reporting;
- GIS;
- drones;
- sensors;
- digital dashboards;
- automated data collection.

The research opportunity is to integrate these capabilities into one operational delay-management framework.

The central research proposition is:

Project delay can be managed more effectively when project-control information, risk information and field/digital information are connected to an early-warning and management-action process.

1.3 Research aim

The aim of this research is:

To develop an integrated digital project-controls and risk-management framework capable of identifying emerging delay risks and supporting timely intervention in major infrastructure projects.

1.4 Research objectives

RO1. Identify major categories of infrastructure-project delay risk.

RO2. Examine the relationship between project controls and risk management.

RO3. Identify digital data sources that can support early warning.

RO4. Develop an integrated delay-risk framework.

RO5. Develop a preliminary Digital Delay Risk Index.

RO6. Define early-warning indicators.

RO7. Demonstrate application through a representative infrastructure-project scenario.

RO8. Establish a methodology for future empirical validation.

1.5 Research questions

RQ1. What are the principal causes of delay in major infrastructure projects?

RQ2. How can project controls support earlier identification of delay risk?

RQ3. How can digital systems improve project-risk visibility?

RQ4. Which indicators provide useful early-warning signals?

RQ5. How can risk probability and schedule impact be integrated?

RQ6. Can an integrated digital framework improve the timeliness of management intervention?

RQ7. How can project-control data be transformed into actionable management information?

2 Conceptual framework

2.1 Conceptual model

The proposed model, the Integrated Digital Project Controls and Risk Framework (IDPCRF), connects schedule, cost, risk, change, interfaces, resources, documents and field data through integrated project intelligence to early warning, management action and delay reduction (Figure 1).

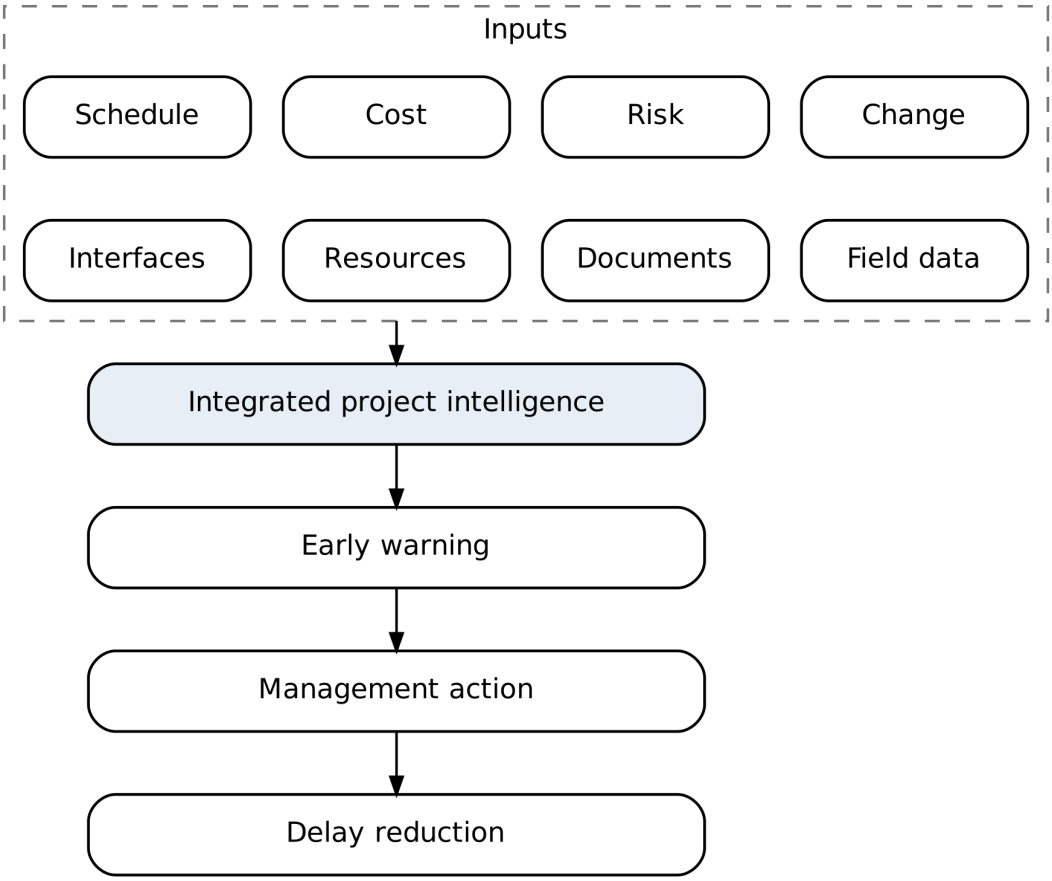


Figure 1. Integrated Digital Project Controls and Risk Framework (IDPCRF).

2.2 Project-control architecture

The framework contains six principal control systems.

2.2.1 Schedule control

Includes:

- baseline schedule;
- WBS;
- activities;
- logic;
- milestones;
- critical path;

- float;
- progress;
- forecast completion.

2.2.2 Cost control

Includes:

- budget;
- commitments;
- actual expenditure;
- forecast;
- change orders;
- cost variance.

2.2.3 Risk control

Includes:

- risk register;
- probability;
- impact;
- risk owner;
- mitigation;
- residual risk;
- trigger events.

2.2.4 Change control

Includes:

- design changes;
- scope changes;
- client instructions;
- variations;
- approval status;
- schedule impact.

2.2.5 Interface control

Includes interfaces between:

- contractors;
- subcontractors;
- engineering;
- procurement;
- utilities;
- authorities;
- operations;

- third parties.

2.2.6 Digital information control

Includes:

- document management;
- field data;
- dashboards;
- BIM;
- GIS;
- drone information;
- photographs;
- mobile reporting.

2.3 Delay classification

The framework proposes the delay categories in Table 1.

Table 1. Proposed delay categories.

Code	Delay category
D01	Design
D02	Procurement
D03	Construction
D04	Resources
D05	Interface
D06	Approval
D07	Access/site
D08	Weather/environment
D09	Safety
D10	Change
D11	Information/documentation
D12	External stakeholder
D13	Logistics
D14	Productivity

This classification should be adapted to the specific project.

2.4 Design delay

Design-related delay may arise from:

- incomplete drawings;
- late drawings;
- design changes;

- conflicting information;
- late approvals;
- RFIs;
- technical clarification;
- design rework.

A useful KPI is:

$$\text{Design resolution time} = \frac{\sum \text{RFI resolution days}}{\text{Number of RFIs}} \quad (1)$$

2.5 Procurement delay

Potential causes include:

- late purchase orders;
- long-lead items;
- supplier problems;
- manufacturing delays;
- inspection delays;
- customs/logistics;
- incomplete specifications.

Potential early-warning indicators:

- procurement milestone slippage;
- supplier schedule variance;
- overdue submittals;
- manufacturing progress;
- delivery-date changes.

2.6 Construction delay

Potential causes include:

- low productivity;
- insufficient resources;
- incomplete work fronts;
- rework;
- poor coordination;
- equipment availability;
- material shortages.

A basic productivity indicator is:

$$\text{Productivity} = \frac{\text{Output}}{\text{Resource input}} \quad (2)$$

2.7 Interface risk

Interface risk is particularly important on large projects.

Examples include the interfaces between:

- civil and mechanical works;
- mechanical and electrical works;
- construction and commissioning;
- contractor and utility provider;
- designer and contractor;
- client and contractor.

An unresolved interface can become a schedule-critical issue.

3 Risk management and the Digital Delay Risk Index

3.1 Risk management framework

The proposed risk-management process is:

Identify → Assess → Assign Owner → Develop Response → Set Trigger → Monitor → Escalate → Close / Transfer / Accept.

3.2 Risk probability and impact

A conventional risk score can be calculated:

$$\text{Risk score} = \text{Probability} \times \text{Impact} \tag{3}$$

For example, with probability = 4/5 and impact = 5/5, the risk score is:

$$4 \times 5 = 20 \tag{4}$$

The numerical thresholds must be established by the individual project.

3.3 Schedule risk

Risk impact should not be considered only as a financial consequence. A risk may affect:

- duration;
- critical path;
- float;
- milestone;
- commissioning;
- handover.

Therefore, schedule exposure should be explicitly recorded.

3.4 Proposed Digital Delay Risk Index

The paper proposes a preliminary Digital Delay Risk Index (DDRI). A conceptual model is:

$$\text{DDRI} = P \times I \times E \times C \tag{5}$$

where P is the probability, I the schedule impact, E the exposure/urgency and C the control weakness.

Each component could be normalized between 0 and 1.

This produces a more dynamic risk assessment than a static risk register.

This formula is a proposed research model and requires empirical validation.

3.5 Control weakness factor

The control weakness factor could consider:

- overdue action;
- missing owner;
- missing mitigation;
- delayed decision;
- incomplete information;
- repeated occurrence.

Examples of the control weakness assigned to different conditions are given in Table 2.

Table 2. Example of control weakness rating.

Condition	Control weakness
Fully controlled	Low
Action overdue	Medium
No effective mitigation	High
Critical decision outstanding	Very high

3.6 Early-warning indicators

The following indicators are proposed.

Schedule:

- SPI;
- critical-path slippage;
- negative float;
- milestone variance;
- look-ahead failure.

Cost:

- cost variance;
- forecast variance;
- change growth;
- commitment trend.

Risk:

- high-risk exposure;
- overdue mitigation;
- repeated risk occurrence.

Engineering:

- overdue drawings;
- overdue RFIs;
- design revisions;
- approval backlog.

Procurement:

- long-lead slippage;
- delayed submittals;
- manufacturing variance.

Construction:

- productivity decline;
- planned-versus-actual quantities;
- incomplete work fronts.

Resources:

- manpower variance;
- equipment availability;
- material shortage.

4 Digital integration and performance control

4.1 Digital data sources

The proposed framework can integrate:

- **Primavera P6.** For schedule planning and control.
- **BIM.** For model-based coordination and information integration.
- **GIS.** For spatial information.
- **Drones.** For visual progress monitoring where permitted.
- **GPS.** For location and survey information.
- **Mobile applications.** For field inspections and progress reporting.
- **Document Management Systems.** For controlled information.
- **Dashboards.** For management visualization.
- **Sensors/IoT.** Where appropriate and justified.

4.2 Digital information flow

The proposed architecture is:

Field → Mobile / Drone / Survey / Inspection → Project Data Platform → Schedule + Cost + Risk + Documents + Procurement → Analytics Engine → Dashboard → Project Manager / Controls Manager → Management Decision → Corrective Action.

4.3 Project dashboard

A project dashboard could include the indicators in Table 3.

Table 3. Example project dashboard.

KPI	Current	Target	Status
Schedule performance	—	1.00	—
Cost performance	—	1.00	—
Critical activities	—	—	—
High risks	—	0	—
Overdue rfis	—	0	—
Procurement delays	—	0	—
Change requests	—	—	—
Productivity	—	Target	—
Safety actions	—	100% closed	—
Interface issues	—	0 overdue	—

Actual values should come from project records.

4.4 Schedule performance

Earned-value methodology can provide established indicators.

4.4.1 Schedule performance index

$$\mathrm{SPI} = \frac{\mathrm{EV}}{\mathrm{PV}} \tag{6}$$

where EV is the earned value and PV the planned value. If SPI = 1.00, performance is theoretically on plan; if SPI < 1.00, progress is behind the planned baseline.

However, SPI should not be treated as the only schedule-health indicator.

4.5 Cost performance

Similarly, the cost performance index is:

$$\mathrm{CPI} = \frac{\mathrm{EV}}{\mathrm{AC}} \tag{7}$$

where EV is the earned value and AC the actual cost. A project can have an acceptable CPI but still have serious schedule risk. Therefore, cost and schedule indicators must be analysed together.

4.6 Look-ahead planning

The framework proposes a rolling three-week or four-week look-ahead, depending on project requirements.

Each activity should be checked for:

- design readiness;

- material readiness;
- manpower;
- equipment;
- access;
- permits;
- predecessor completion;
- safety readiness.

An activity that appears in the schedule but lacks prerequisites should be flagged before it reaches execution.

4.7 Constraint management

A key feature of the framework is a constraint register. Possible constraints are:

- drawing;
- material;
- manpower;
- equipment;
- access;
- permit;
- inspection;
- approval;
- utility;
- safety;
- survey;
- stakeholder decision.

Each constraint should have:

- owner;
- required date;
- actual date;
- status;
- impact;
- escalation level.

4.8 Constraint closure rate

A potential KPI is:

$$\text{CCR} = \frac{\text{Constraints closed on time}}{\text{Total constraints}} \times 100 \tag{8}$$

This gives management a simple indication of whether the project is removing barriers quickly enough.

4.9 Risk-to-schedule link

The framework recommends connecting each significant risk to:

- affected activity;
- responsible owner;
- milestone;
- potential delay;
- mitigation;
- trigger;
- contingency.

Therefore, the risk register should not remain an isolated document. It should connect directly to the schedule, cost, actions and dashboard.

4.10 Change management

Changes are a major potential source of delay. The proposed process is:

Change Identified → Technical Assessment → Cost Assessment → Schedule Assessment → Risk Assessment → Approval → Implementation → Baseline Update.

A change should not simply be added to the schedule without understanding its consequences.

4.11 Document-control integration

The framework proposes connecting the following with relevant project activities:

- drawings;
- specifications;
- RFIs;
- technical queries;
- approvals;
- transmittals;
- inspection records.

This allows managers to answer the question: which unresolved document issue is threatening a critical activity?

4.12 Artificial intelligence opportunity

A future version of the system could use AI/analytics to identify patterns such as:

- repeated delays;
- abnormal productivity;
- overdue actions;
- recurring RFIs;
- supplier slippage;
- escalating risks;
- interface congestion.

The AI should act as a decision-support mechanism, not as an autonomous authority. Human project professionals should verify critical alerts.

4.13 Predictive delay model

Future empirical research could develop:

$$P(\text{Delay}) = f(\text{Risk},\ \text{Schedule},\ \text{Resources},\ \text{Design},\ \text{Procurement},\ \text{Interfaces},\ \text{Change}) \tag{9}$$

Potential statistical methods include:

- logistic regression;
- survival analysis;
- decision trees;
- random forests;
- gradient boosting;
- Bayesian models.

The selected model should be determined by the quality and size of the dataset.

5 Illustrative application

5.1 Representative case scenario

Consider a major infrastructure work package whose baseline requires 100 activities. During weekly monitoring:

- 12 activities show negative float;
- 8 have overdue engineering information;
- 5 have procurement concerns;
- 4 have unresolved interfaces;
- 3 have manpower shortages.

A conventional report may simply state: "Progress is behind schedule." The proposed system instead identifies the underlying risk chain.

5.2 Example risk chain

An example risk chain is: Late Drawing → Delayed Material Approval → Procurement Delay → Work-front Unavailable → Manpower Underutilization → Productivity Loss → Critical Activity Delay → Milestone Risk.

This is more actionable than simply reporting percentage progress.

5.3 Illustrative digital alert

Suppose the system identifies the following:

- **Activity:** Pipeline Section X;
- **Baseline start:** Day 100;
- **Required drawing:** Day 90;

- **Drawing status:** Not approved;
- **Material status:** Procurement not released;
- **Float:** 3 days;
- **Risk:** High.

The system generates the alert "HIGH DELAY RISK — Management intervention required." This should trigger:

- engineering escalation;
- procurement review;
- project-controls review;
- responsible-manager assignment;
- recovery plan.

5.4 Delay avoidance concept

The proposed framework distinguishes **delay avoidance** (intervention before the delay occurs) from **delay recovery** (action after the delay has occurred). This distinction is important. The framework's primary objective is: avoid → detect early → mitigate → recover, rather than: delay → report → explain.

5.5 Recovery planning

When a delay occurs, potential recovery options include:

- resequencing;
- additional resources;
- overtime where appropriate;
- alternative work fronts;
- acceleration;
- parallel activities;
- revised procurement strategy;
- design prioritization.

Any recovery strategy must be evaluated for:

- safety;
- quality;
- cost;
- contractual implications;
- feasibility.

5.6 Root-cause analysis

The framework recommends using the 5 Whys and/or fishbone analysis. For example:

- Why was activity delayed? Material unavailable.
- Why? Purchase order late.
- Why? Technical approval late.

- Why? Design information incomplete.
- Why? Design coordination issue.

The actual root cause may therefore be design coordination rather than procurement.

5.7 Lessons-learned system

After each significant delay, the following sequence should be recorded: Cause → Impact → Response → Effectiveness → Lesson → Preventive Control.

Lessons should be converted into future project controls rather than simply stored in a database.

5.8 Proposed integrated framework

The complete system is shown in Figure 2.

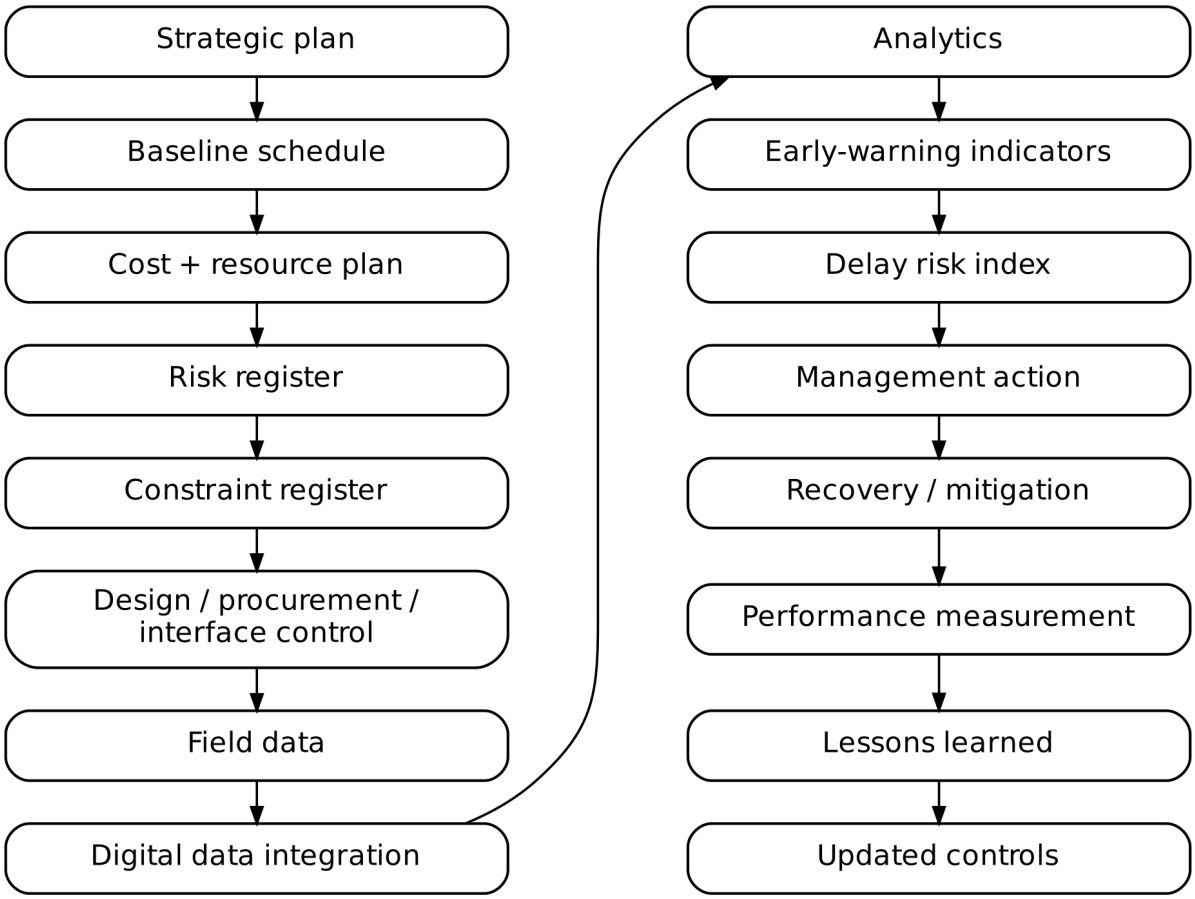


Figure 2. Proposed integrated framework.

5.9 Proposed performance indicators

Schedule:

- SPI;
- milestone variance;
- critical-path variance;
- float erosion;
- forecast completion.

Risk:

- high risks;
- overdue mitigation;
- risk exposure;
- emerging risks.

Engineering:

- overdue drawings;
- RFIs;
- approval time;
- design changes.

Procurement:

- procurement milestone variance;
- supplier performance;
- long-lead status.

Construction:

- productivity;
- planned versus actual quantity;
- work-front availability.

Management:

- overdue actions;
- decision turnaround time;
- constraint closure.

5.10 Management response levels

The framework could use four levels.

- **Green.** Normal performance.
- **Amber.** Emerging risk requiring monitoring.
- **Red.** Significant risk requiring management intervention.
- **Critical.** Potential threat to major milestone or project objective requiring executive escalation. These thresholds should be calibrated using actual project data.

6 Research proposition and proposed empirical validation

6.1 Research proposition

The central proposition is:

An integrated project-controls system that connects schedule, cost, risk, change, constraints, interfaces and digital field information can provide earlier identification of delay threats than isolated periodic reporting.

This proposition should subsequently be tested empirically.

6.2 Hypotheses

H_1. Greater integration of project-control data is associated with earlier identification of schedule risk.

H_2. Higher-quality risk monitoring is associated with reduced delay exposure.

H_3. Digital field-data integration improves the timeliness of project-status information.

H_4. Early-warning systems are associated with faster management response.

H_5. Faster management response is associated with lower realized schedule impact.

H_6. Integrated project controls improve delay-management performance compared with fragmented control systems.

6.3 Proposed empirical method

A future study could use:

- **Phase 1.** Survey construction professionals.
- **Phase 2.** Collect project-level historical data.
- **Phase 3.** Identify delay events.
- **Phase 4.** Compare early-warning identified events versus late-detected events.
- **Phase 5.** Measure:
- warning lead time;
- intervention time;
- delay duration;
- recovery duration.

6.4 Key new metric: warning lead time

The framework proposes:

$$\mathrm{WLT} = T_{\mathrm{Delay}} - T_{\mathrm{Warning}} \tag{10}$$

where T_{Delay} is the date the delay actually occurred and T_{Warning} the date the risk was identified.

A positive warning lead time indicates that management had an opportunity to intervene before the delay.

This is potentially one of the most valuable empirical measures in the research.

6.5 Intervention effectiveness

Another proposed metric is:

$$\mathrm{IE} = \frac{\text{Potential delay} - \text{Actual delay}}{\text{Potential delay}} \times 100 \tag{11}$$

For example, if a risk was estimated to cause 20 days of delay but only 5 days occurred after intervention:

$$\text{IE} = \frac{20 - 5}{20} \times 100 = 75\% \tag{12}$$

This is illustrative only.

The methodology for estimating "potential delay" would need to be standardized before empirical use.

6.6 Digital maturity

Projects could also be assessed according to digital maturity (Table 4).

Table 4. Proposed digital maturity levels.

Level	Description
Level 1 — Manual	Paper/spreadsheet reporting
Level 2 — Digital documents	Electronic document management
Level 3 — Integrated	Schedule, cost and risk connected
Level 4 — Analytical	Dashboards and predictive analytics
Level 5 — Predictive	Real-time data + advanced analytics + proactive intervention

The maturity model is proposed and requires validation.

7 Application, benefits and limitations

7.1 Practical application to Saudi infrastructure

The framework is particularly applicable to large Saudi infrastructure projects because these projects may involve:

- multiple contractors;
- international consultants;
- major engineering packages;
- complex interfaces;
- large workforces;
- extensive procurement;
- regulatory stakeholders;
- significant documentation;
- geographically dispersed work.

The framework is therefore designed to operate at project, package, contract and workfront levels.

7.2 Benefits of the framework

Potential benefits include:

1. **Earlier warning.** Problems can be identified before major schedule impact.
2. **Better visibility.** Managers can see relationships between risks and activities.
3. **Faster decisions.** Outstanding actions can be escalated.

4. **Better accountability.** Each risk and constraint has an owner.
5. **Improved coordination.** Engineering, procurement and construction information can be connected.
6. **Better lessons learned.** Actual causes can be captured and reused.

7.3 Limitations

The proposed framework has several limitations.

1. The DDRI has not yet been empirically validated.
2. Digital integration depends on data quality.
3. Poor-quality schedules can produce misleading analytics.
4. Different projects have different risk profiles.
5. AI predictions require sufficient historical data.
6. Digital systems cannot replace professional judgement.
7. Some project information may be commercially or contractually confidential.

7.4 Data governance

A digital project-control framework must establish:

- data ownership;
- access rights;
- version control;
- data quality;
- audit trails;
- cybersecurity;
- confidentiality;
- retention.

A dashboard is only as reliable as its underlying data. Therefore, data quality is a project-control requirement, not merely an IT requirement.

7.5 Data quality framework

Before analytics are performed, the following should be checked:

- **Completeness.** Are required fields populated?
- **Accuracy.** Does the information represent the actual condition?
- **Timeliness.** Is the data current?
- **Consistency.** Do different systems agree?
- **Traceability.** Can the source be identified?

7.6 Digital transformation principle

The research does not argue that "technology automatically reduces delay". Instead, technology can improve the availability, timeliness and integration of information, which can support better management decisions. Actual delay reduction depends on:

- management;
- organizational capability;
- data quality;
- processes;
- resources;
- decision authority.

8 Discussion

The proposed IDPCRF addresses an important weakness in traditional project reporting: the separation of project information into functional silos.

A schedule may identify an activity as late. A risk register may identify a procurement risk. A document system may show an overdue approval. A field report may show that the workfront is unavailable.

If these systems remain disconnected, management may not recognize that they describe the same emerging delay event.

The proposed framework connects these signals.

8.1 From reporting to prediction

Traditional reporting asks "What happened?". The proposed approach asks "What is happening?", then "What is likely to happen?" and finally "What should management do now?". This represents the fundamental conceptual transition of the paper.

8.2 Theoretical contribution

The research contributes:

1. **Integrated project-control architecture.** Schedule, cost, risk and digital information are treated as connected systems.
2. **Digital Delay Risk Index.** A proposed method for prioritizing emerging delay threats.
3. **Warning Lead Time.** A proposed measure of how early management identifies delay risk.
4. **Intervention Effectiveness.** A proposed measure of whether intervention reduced potential schedule impact.

8.3 Practical contribution

The framework can potentially be implemented through a project dashboard incorporating schedule, cost, risk, engineering, procurement, resources, interfaces, constraints, field progress and management actions. This provides a single management view.

8.4 Recommended implementation roadmap

1. Develop project WBS.
2. Establish baseline schedule.
3. Create integrated risk register.
4. Create constraint register.
5. Link risks to schedule activities.
6. Link risks to schedule activities.
7. Integrate engineering/procurement data.
8. Collect field data digitally.
9. Build dashboard.
10. Establish early-warning thresholds.
11. Measure intervention.
12. Record lessons learned.
13. Continuously improve the system.

9 Conclusion

Delay in major infrastructure projects is rarely caused by a single isolated factor. Design, procurement, resources, interfaces, approvals, changes, information and construction activities can interact to produce schedule impacts.

This research proposes an Integrated Digital Project Controls and Risk Management Framework (IDPCRF) designed to connect these elements.

The framework combines schedule control, cost control, risk management, change management, constraint management, interface management, digital information and field data, leading to early warning, management intervention and delay reduction.

A preliminary Digital Delay Risk Index (DDRI) and Warning Lead Time (WLT) concept are introduced as potential quantitative measures.

The principal research proposition is that integrated information and early intervention can improve the management of emerging delay risks. However, this proposition requires empirical testing.

Future research should therefore collect historical and real-time project data, validate the proposed indicators, establish appropriate weighting methods and compare integrated versus fragmented project-control environments.

The ultimate objective is to move infrastructure project management from “report the delay after it happens” towards “identify the risk early, intervene before it becomes a delay, and measure whether the intervention worked”.

Declarations

Author contribution: Conceptualization; construction-management perspective; project-controls framework development; risk-management framework; digital project-control architecture; delay-management methodology; conceptual model; manuscript preparation and review.

Conflict of interest: The author declares no competing interests directly related to this research.

Funding: This research received no specific external funding.

Data availability: This framework-development manuscript does not report project data or empirical results. Future empirical validation should use appropriately authorized project records, survey data or anonymized datasets subject to applicable confidentiality and research-ethics requirements.

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