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A Digital Twin Framework for Real-Time Schedule Monitoring and Re-Optimization in Saudi Construction Mega-Projects

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Abstract

Construction schedules on large projects are usually updated from periodic progress reports, so deviations are recognised days or weeks after they begin. This paper proposes a digital twin framework that closes the loop between the site and the schedule for Saudi mega-projects delivered under Vision 2030. The framework has five layers, covering the physical site, data acquisition, an integrated 4D twin model, analytics and optimization, and decision services. It operates as a six-step cycle of sensing, synchronization, deviation detection, forecasting, re-optimization and instruction, with defined indicators and trigger thresholds. Re-optimization is carried out by testing candidate recovery plans in the twin before one is issued. To illustrate the mechanism, a synthetic project of 48 activities was simulated over 500 runs under four control policies. In this illustrative experiment, mean completion delay fell from 34.4 working days under fortnightly reporting to 11.1 days under daily twin monitoring and to 4.3 days when re-optimization was added. These figures are simulation outputs under stated assumptions and are not field evidence. The paper also sets out an implementation roadmap, the main barriers reported for the Kingdom, and the alignment of the framework with Vision 2030.

Index Terms: 4D BIM, Digital Twin, Schedule Re-Optimization, Saudi Arabia, Vision 2030

I. INTRODUCTION

Vision 2030 commits Saudi Arabia to a construction programme of exceptional size [1]. An industry study reported in 2025 counted 577 major programmes in the Kingdom and a 643% rise in active megaprojects since 2010 [2]. Projects of this size have a poor record of finishing on time anywhere in the world [3], and the Kingdom's own construction sector has a long-documented delay problem: a survey of the Eastern Province found time overrun in 70% of projects [4], and a later study of government-funded buildings identified late payment, change orders, ineffective planning and scheduling, and poor site management among the leading causes [5].

Many of these causes share a feature. They develop during execution, and their effect on the schedule grows while they go unnoticed. Conventional project control does not see them quickly. The critical path method [6] produces a baseline, progress is measured by site staff and compiled into weekly or monthly reports, and the schedule is revised after the report is reviewed. Between one report and the next, the plan that crews are working to may already be out of date.

A digital twin offers a different arrangement. In its original sense, a digital twin is a virtual counterpart of a physical system that is kept consistent with it through a continuing exchange of data [7], [8]. For a construction project, the physical system is the site and the virtual counterpart is a 4D model that links building elements to schedule activities. If site data update that model automatically, and if the model is

used to test and issue revised plans, the delay between an event and the response to it can shrink from weeks to days.

Research on construction digital twins has grown quickly [9], [10], [11], and automated progress monitoring is now technically mature enough to feed such a twin [12], [13]. The return path is less developed. Reviews find that vision-based monitoring remains weakly connected to construction management decisions [12], and that the translation of predictions into proactive time management is underexplored [14]. In Saudi Arabia, studies of digital twins have so far examined perceptions, readiness and success factors, and have not proposed an operational framework for schedule control [15], [16], [17]. This paper addresses that gap. Its objectives are: (1) to define a digital twin framework for real-time schedule monitoring and re-optimization, including its architecture, operating cycle, indicators and trigger rules; (2) to illustrate, through a simulation on a synthetic project, how monitoring frequency and re-optimization affect completion delay; and (3) to set out how the framework can be implemented in the Saudi context and how it supports Vision 2030. The paper is conceptual. The simulation demonstrates the mechanism under stated assumptions and does not substitute for validation on a live project.

II. BACKGROUND AND RELATED WORK

A. Digital twins and levels of integration

The term digital twin is used loosely in construction, and it is useful to separate three levels by the direction and automation of data flow [18]. A digital model exchanges data with the physical object by hand. A digital shadow receives data from the physical object automatically, with the return flow still manual. A digital twin has automatic flow in both directions. Fig. 1 and Table I apply this classification to schedule control. Most current practice, including 4D BIM used for visualisation and coordination [19], sits at the first level.

Construction-specific work has developed the concept further. One line of research sets out the semantic and data requirements of a construction digital twin [9]. Another describes construction managed through digital twin information systems, in which monitoring, interpretation and planning form a closed control loop [10]. Literature reviews confirm rapid growth of applications across the project life cycle [11], and a recent systematic review finds that implementation is still fragmented and uneven across life-cycle phases and organisational contexts [20].

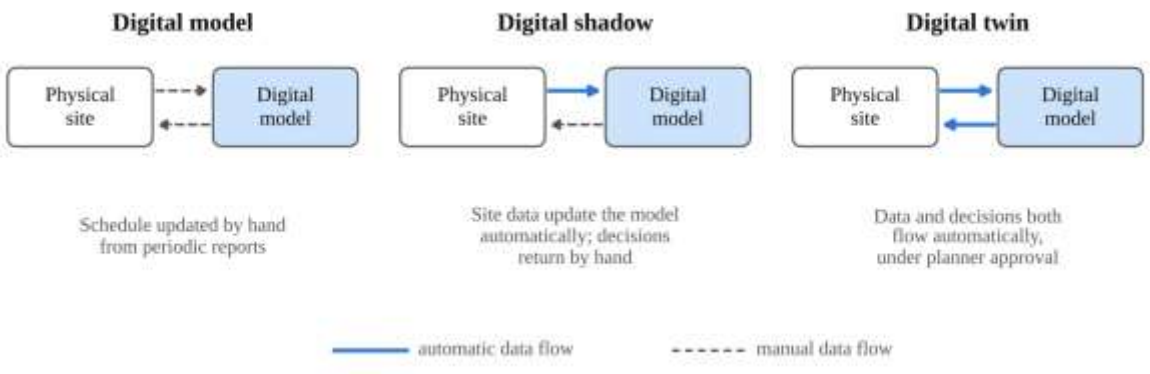


Fig. 1. Three levels of site-to-model integration applied to schedule control, following the classification in [18].

TABLE I. LEVELS OF INTEGRATION AND THEIR MEANING FOR SCHEDULE CONTROL

Level	Site to model	Model to site	Typical schedule practice
Digital model	Manual entry from progress reports	Manual; revised programme issued periodically	Baseline schedule and 4D model updated weekly or monthly
Digital shadow	Automatic from site capture and logs	Manual; planner interprets dashboards	Near-real-time progress view; re-planning still periodic
Digital twin	Automatic from site capture and logs	Automatic generation of recovery plans, issued after planner approval	Continuous monitoring with event-driven re-optimization

B. Automated progress monitoring

The upward data flow depends on measuring progress without manual survey. An influential approach reconstructs the as-built scene from unordered daily site photographs and compares it with an IFC-based model to infer which elements are complete [21]. A systematic review of computer-vision-based monitoring describes four sub-processes, namely data acquisition, information retrieval, progress estimation and output visualisation, and observes that most techniques still need human intervention [12]. A broader review lists laser scanning, uncrewed aerial systems, RFID, computer vision and BIM among the main tools and identifies limited generalisation, data quality, data integration and real-time operation as the principal challenges [13]. A recent study links this monitoring directly to a twin: 3D point clouds are compared with the BIM model to track activity status and to predict completion, and the result is displayed as a Gantt chart [22].

C. Forecasting and schedule re-optimization

Once progress is known, two further steps are needed. The first is forecasting. Earned schedule expresses schedule performance in units of time [23], and machine learning methods have been applied to forecast final duration from periodic control data [24]. The second is revising the plan. Construction scheduling has a large optimization literature covering mathematical, heuristic and metaheuristic methods [25]; priority-rule heuristics remain a practical baseline for resource-constrained scheduling [26], and multi-objective genetic algorithms such as NSGA-II are widely used when time is traded against cost or other objectives [27]. A review of artificial intelligence in construction finds genetic algorithms to be the main optimization tool in time management [14].

Scheduling under uncertainty distinguishes proactive methods, which build protection into the baseline, from reactive methods, which revise the schedule when disruptions occur [28]. Rescheduling policies are commonly classed as periodic, event-driven or hybrid [29]. Manufacturing research has already combined these ideas with digital twins: studies use the twin to detect anomalies and trigger rescheduling of a job shop [30] and to learn dynamic scheduling policies with reinforcement learning [31]. Construction examples are fewer. One framework integrates BIM, IoT data and data mining to discover bottlenecks and

predict task progress [32], and a recent preprint combines reality capture, computer-vision progress measurement and probabilistic scheduling in a 4D/5D twin, while noting that weak feedback loops to scheduling systems still limit real-time control [33].

D. The Saudi context

Evidence on digital twins in the Kingdom is recent. A survey of 106 architecture, engineering and construction professionals found that the highest-ranked challenge to AI-based digital twins was the lack of standardisation, followed by limited understanding of AI capabilities and limited IT infrastructure [15]. A structural equation model of BIM and digital twin readiness has been developed for the Egyptian and Gulf construction sectors [16]. A master's study at a Saudi university tested sixteen hypotheses relating four groups of digital twin features to project success and validated its framework through two case studies [17]. BIM, on which any construction twin depends, is itself described as relatively new in the Saudi building sector [34]. International work on critical success factors for digital twin implementation provides a wider reference point [35].

E. Research gap

Table II compares representative studies by what they sense, what they predict and how they respond. The components exist separately. Progress can be captured automatically, completion can be forecast, and schedules can be optimized. What is not available, and in particular not for the Saudi mega-project setting, is a specification that connects them into one operating cycle with explicit triggers, decision rights and a path to implementation. The framework in Section III is intended to provide it.

TABLE II. REPRESENTATIVE RELATED WORK COMPARED WITH THE PROPOSED FRAMEWORK

Study	Domain	Site sensing	Forecasting	Schedule response
Golparvar-Fard et al. [21]	Building construction	Daily photographs compared with IFC model	Not the focus	Not addressed
Pan and Zhang [32]	Construction	BIM and IoT data with data mining	Task progress prediction	Bottleneck identification
Mathew et al. [22]	Construction	Point clouds compared with BIM	Projected completion dates	Status shown on Gantt chart
Khoshkonesh et al. [33]	Mid-rise building	Photogrammetry, LiDAR and site imagery	Probabilistic schedule analysis	Schedule control; feedback loops noted as a limitation
Li et al. [30]; Yan et al. [31]	Manufacturing	Shop-floor state in twin	Anomaly detection	Dynamic rescheduling
This paper	Construction mega-projects	Multi-source capture into 4D twin	Earned schedule and completion forecast	Triggered re-optimization tested in the twin, with approval workflow

III. PROPOSED FRAMEWORK

A. Design requirements

Five requirements follow from the review and from the Saudi delay evidence. The twin must be driven by the schedule, so that every sensed quantity maps to an activity. It must draw on commercial and administrative records as well as physical capture, because payment, approval and change-order problems are leading causes of delay in the Kingdom [5]. It must respond to events as well as to the calendar [29]. It must keep the planner in control of decisions that carry contractual consequences. It must rest on a managed information environment of the kind described in ISO 19650 [36].

B. Architecture

Fig. 2 shows the five-layer architecture. The physical layer comprises work zones and building elements, crews, equipment and materials. The data acquisition layer gathers observations from the sources listed in Table III. The integration layer holds the twin model: the 4D BIM model, the schedule network, the as-built state of each element, resource and constraint data, and the common data environment that governs them. The analytics layer estimates progress, detects deviation, forecasts completion, runs what-if simulations and re-optimizes the schedule. The decision layer presents dashboards, issues the look-ahead plan, raises alerts and routes changes for approval. A governance function covering data standards, access control and cybersecurity spans all layers.

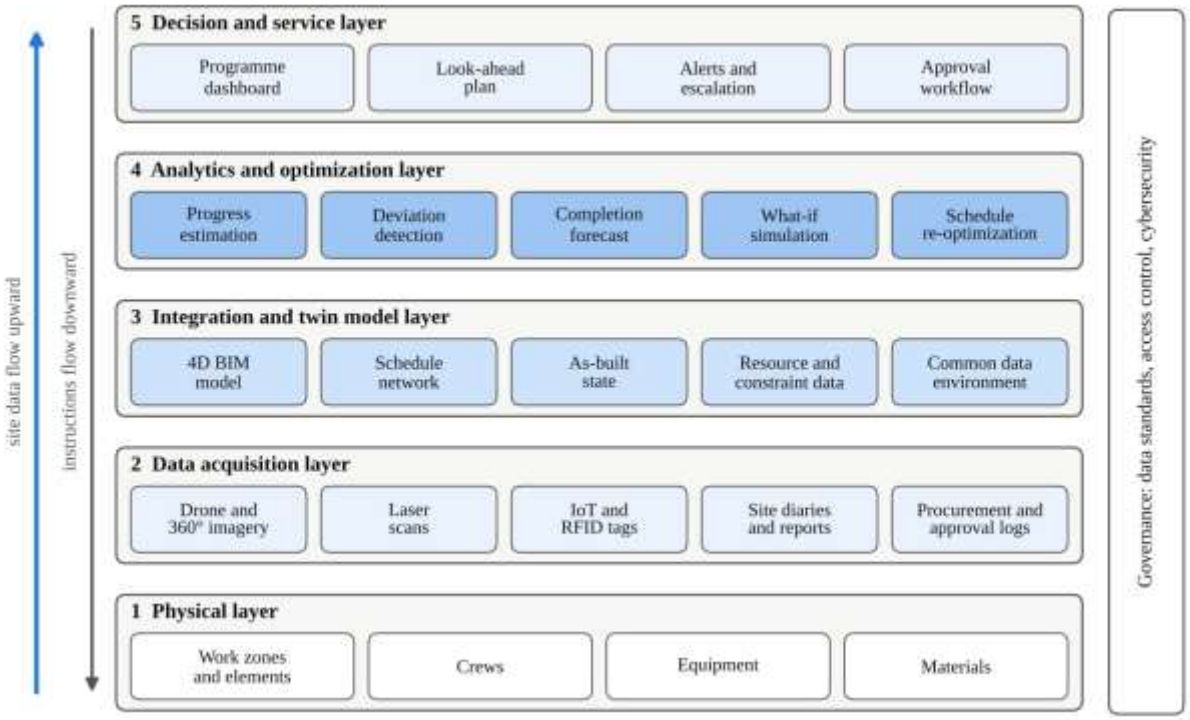


Fig. 2. Five-layer architecture of the proposed digital twin framework.

TABLE III. DATA SOURCES FOR THE ACQUISITION LAYER

Source	Information provided	Suggested update	Twin element updated
Drone and 360° imagery	Visible completion of structure, envelope and external works	Daily to weekly	As-built state of elements

Source	Information provided	Suggested update	Twin element updated
Laser scans	Geometry of installed work; dimensional conformity	At milestones	As-built state; quality records
IoT and RFID tags	Location and status of materials, prefabricated units and equipment	Continuous	Resource and constraint data
Site diaries and daily reports	Crew numbers, work performed, stoppages and their causes	Daily	Activity progress; hold register
Procurement and logistics records	Order, fabrication and delivery dates	Daily	Material constraints
Approval, RFI and payment logs	Open submittals, inspections, change orders and payment status	Daily	Hold register; activity constraints

C. Operating cycle

The framework runs as the six-step cycle in Fig. 3. In the sensing step, site state is captured from the sources in Table III. In the synchronization step, observations are mapped to elements and activities and the twin is updated. In the detection step, actual progress is compared with the plan using the indicators defined below. In the forecasting step, completion dates are projected for the project and for each milestone. In the re-optimization step, candidate recovery plans are generated and tested in the twin. In the final step, the selected plan is approved and issued to site as a revised look-ahead. The cycle repeats daily, and it is also started immediately when a hold or change is recorded. This is a hybrid rescheduling policy in the sense used in the scheduling literature [29].

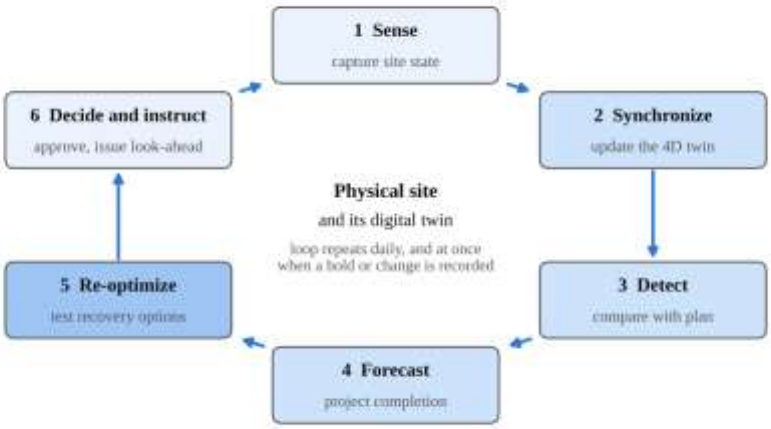


Fig. 3. Six-step operating cycle linking the site and its digital twin.

D. Indicators and triggers

Deviation is measured with earned schedule [23]. For a status date AT, the earned schedule ES is the time at which the baseline planned the progress that has been achieved. The time-based schedule performance index is

$$SPI(t) = ES / AT$$

and the schedule lag is AT − ES. Values of SPI(t) below one indicate that the project is behind plan. Table IV lists the indicators used by the framework and the conditions that trigger re-optimization. The numerical thresholds are starting values that an owner should calibrate to its own tolerance.

Fig. 4 shows the decision logic. When no trigger is met, the current plan continues. When a trigger is met, candidate recovery plans are generated and simulated, and the plan with the earliest forecast finish is selected. A plan that only resequences work or reallocates crews within the contractor's existing resources lies within the planner's authority and is issued directly. A plan that requires overtime beyond an agreed allowance, additional resources or a change to contractual milestones is escalated for approval before it is issued.

TABLE IV. INDICATORS AND TRIGGER CONDITIONS

Indicator	Definition	Trigger for re-optimization (starting value)
Schedule performance index, SPI(t)	Earned schedule divided by actual time	Below 0.95 on two consecutive updates
Forecast completion slip	Forecast finish minus baseline finish, in working days	More than 5 working days
Open hold	Activity stopped by a missing approval, material, inspection or payment	Any hold on a critical or near-critical activity
Crew standby	Crew-days assigned to work that cannot proceed	Any standby longer than one day
Float consumption	Reduction in total float of an activity since the last update	Float falls below 3 working days

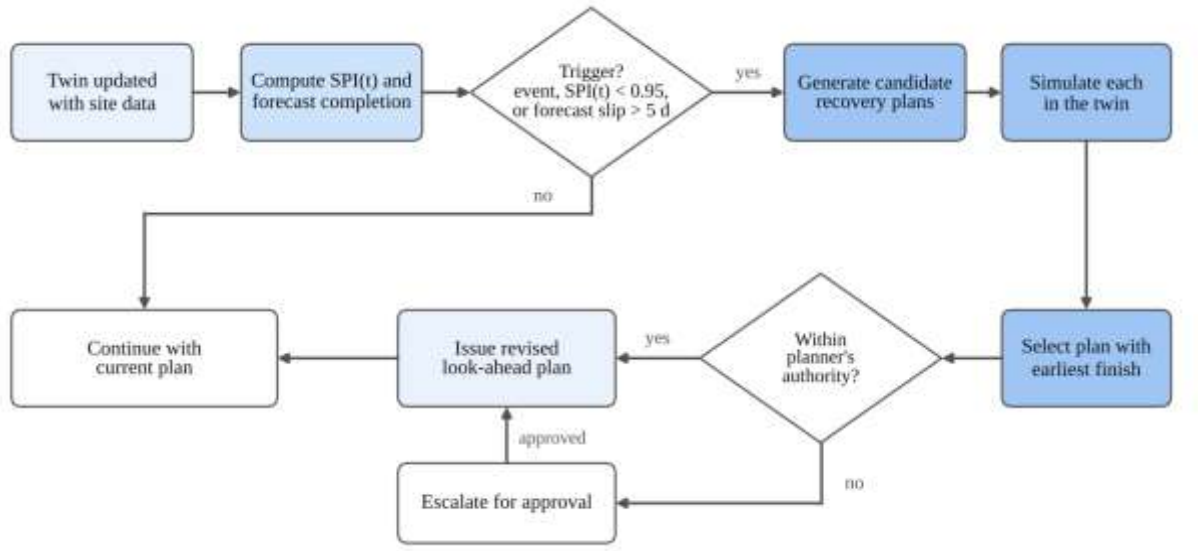


Fig. 4. Trigger and re-optimization logic. SPI(t) is the time-based schedule performance index.

E. Re-optimization model

Re-optimization is posed as a resource-constrained scheduling problem on the remaining work. The decision variables are the priority order in which ready activities receive crews and the activities to which

a limited acceleration allowance is applied. The primary objective is to minimise forecast completion time; cost and the number of changes to the issued plan can be added as further objectives and handled with a multi-objective method such as NSGA-II [27]. The constraints are precedence relations, crew availability by trade, activities currently on hold with their expected release dates, and the acceleration allowance. Each candidate is evaluated by running it forward in the twin from the current state, so the comparison reflects the project as it stands and not the baseline. The framework does not prescribe a solver. Priority-rule heuristics [26] are adequate for daily use, and metaheuristic or learning-based methods [31] can be substituted where computing time allows.

IV. ILLUSTRATIVE SIMULATION

A. Purpose and scope

A simulation was carried out to illustrate how the two features that distinguish the framework, frequent synchronization and re-optimization, affect completion time. The project is synthetic and the parameter values are assumptions chosen to be plausible. The results show the direction and relative size of effects under those assumptions. They are not measurements from a real project and should not be quoted as expected savings.

B. Synthetic project and disturbances

The project has 6 work zones, each with 8 activities in sequence (substructure, structure, envelope, MEP rough-in, partitions, MEP fit-out, finishes and commissioning), giving 48 activities and 633 planned crew-days. Four crew types serve the activities, with two civil, one envelope, two MEP and two finishing crews. The baseline plan in Fig. 5 was produced by a priority-rule schedule under these crew limits and finishes on working day 192.

Two kinds of disturbance were applied. Daily crew productivity varies at random around a mean slightly below the planned rate. In addition, each activity has a 30% chance of a hold, representing a missing approval, material or inspection, which stops the activity at a random point in its progress; on average 14.4 holds occurred per run. A hold takes 4 to 12 working days to resolve, counted from the day it is detected at a progress update. A crew assigned to a held activity stands by until the hold is detected or, failing that, until a site supervisor redeploys it after 5 days. Table V gives the parameters.

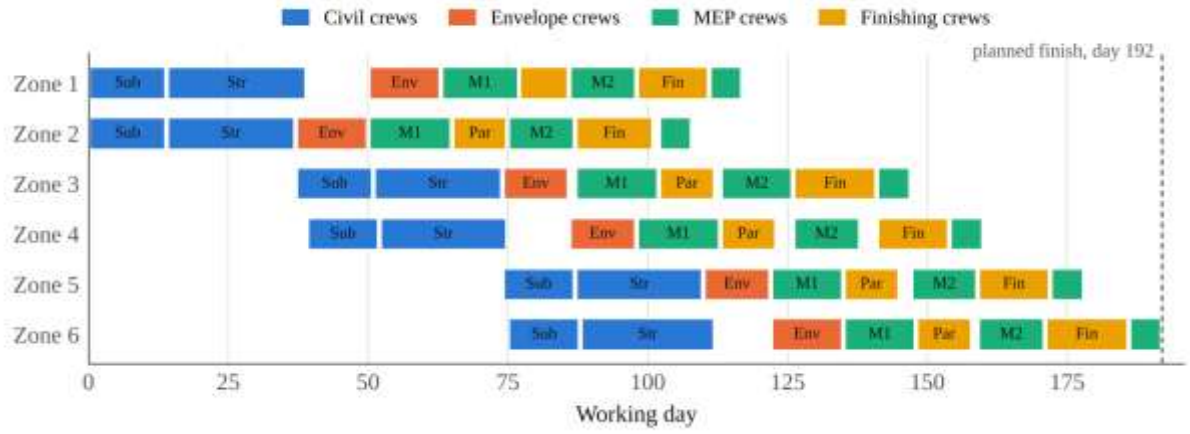


Fig. 5. Baseline plan of the synthetic project. Sub = substructure, Str = structure, Env = envelope, M1 = MEP rough-in, Par = partitions, M2 = MEP fit-out, Fin = finishes; the last bar in each zone is commissioning.

TABLE V. SIMULATION PARAMETERS (ASSUMED VALUES)

Parameter	Value	Note
Activities; work zones	48; 6	Eight trades in sequence per zone
Crews (civil, envelope, MEP, finishing)	2, 1, 2, 2	One crew per activity
Baseline duration	192 working days	Planned productivity 1.0, no overtime
Daily productivity factor	Lognormal, mean 0.95, log-sd 0.25	Independent by activity and day
Probability of a hold per activity	30%	Starts at 10–80% progress
Hold resolution time	4–12 working days	Counted from detection
Supervisor redeployment of standby crew	After 5 days	Applies when the hold is not yet detected
Overtime	Factor 1.25 on up to 2 activities	Same allowance in all policies
Candidate plans per re-optimization	10	Policy D only
Replications	500	Same random disturbances applied to every policy

TABLE VI. CONTROL POLICIES COMPARED

Policy	Description	Progress update	Crew priority
A	Fortnightly reporting	Every 14 days	Baseline sequence
B	Weekly reporting	Every 7 days	Baseline sequence
C	Digital twin, monitoring only	Daily	Baseline sequence
D	Digital twin with re-optimization	Daily	Best of candidate plans tested in the twin, on each event and at least weekly

C. Control policies

Table VI defines four policies. Policies A and B represent conventional control with fortnightly and weekly progress updates. Policy C represents a digital shadow: the twin is synchronized daily, so holds are detected and standby crews are released within a day, and crews continue to follow the baseline sequence. Policy D adds re-optimization. Whenever a hold is detected or cleared, and at least once a week, 10 candidate priority lists are run forward in the twin and the one with the earliest finish is adopted; on average this happened 42.1 times per run. The candidates comprise the current list, the baseline sequence, a list ordered by updated total float, and random perturbations of the best of these. All four policies have the same overtime allowance, so the comparison isolates the effect of information and re-planning.

D. Results

Table VII and Fig. 6 summarise the results. Under fortnightly reporting the project finished 34.4 working days late on average, or 17.9% over the baseline. Weekly reporting reduced the mean delay to 22.9 days. Daily synchronization without re-optimization reduced it to 11.1 days, and it removed crew standby on held work, which averaged 47.6 crew-days per run under policy A. Adding re-optimization reduced the mean delay to 4.3 days, or 2.2%.

Because every policy faced the same random disturbances in each run, the policies can be compared run by run. Policy D finished earlier than policy C in 83.6% of runs, on the same day in 3.4% and later in 13.0%, with a mean difference of 6.8 days. Re-optimization is therefore beneficial on average and is not guaranteed to help in every case, since each plan is chosen on expected productivity and future holds are unknown when it is chosen.

Fig. 6(a) follows one run. All policies begin slightly ahead of the baseline because the baseline assumes no overtime. The policies separate as holds accumulate: under policies A and B the lag grows in steps as holds wait for the next update, and under policy D the lag stays close to zero. Fig. 7(a) shows that mean delay rises steadily with the interval between updates, from 11.1 days at a one-day interval to 22.9 days at seven days and 54.7 days at twenty-eight days. Fig. 7(b) shows the share of runs that finished within 5% and 10% of the planned duration: 5% and 18% for policy A, against 74% and 94% for policy D.

TABLE VII. SIMULATION RESULTS OVER 500 RUNS (BASELINE DURATION 192 WORKING DAYS)

Policy	Mean duration (days)	Mean delay (days)	SD of delay	Delay P10 / P50 / P90 (days)	Mean delay (%)	Crew standby (crew-days)	Runs within 5% / 10% (%)
A	226.4	34.4	15.8	15.0 / 32.0 / 56.0	17.9	47.6	5 / 18
B	214.9	22.9	12.1	8.0 / 22.0 / 40.0	12.0	37.2	12 / 44
C	203.1	11.1	9.2	0.0 / 10.0 / 24.0	5.8	0.0	47 / 81
D	196.3	4.3	8.9	-7.0 / 3.0 / 16.0	2.2	0.0	74 / 94

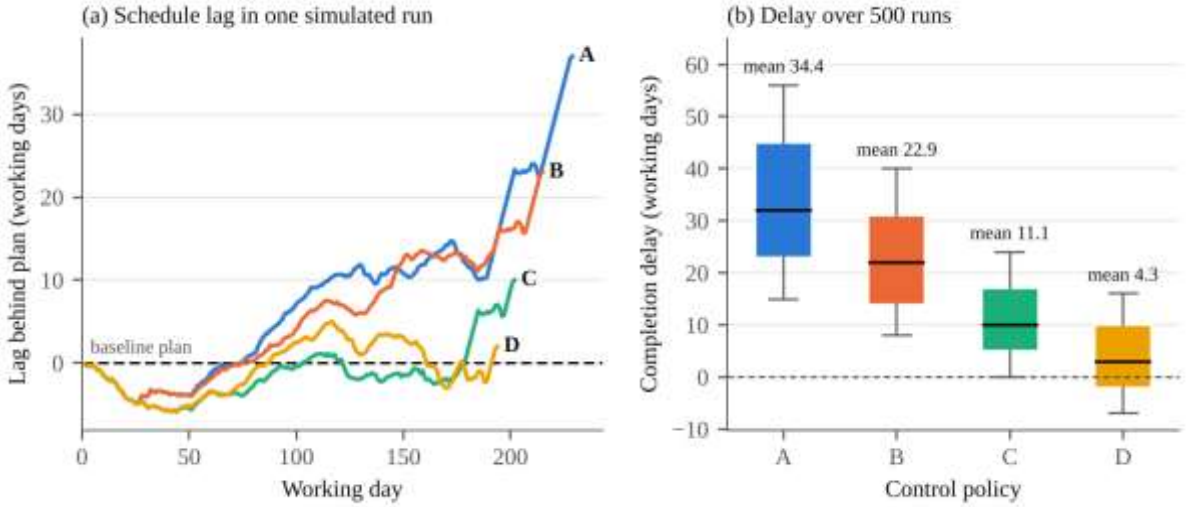


Fig. 6. Simulation results. (a) Schedule lag behind the baseline plan in one run under each policy. (b) Distribution of completion delay over 500 runs; boxes show the 25th to 75th percentiles and whiskers the 10th to 90th.

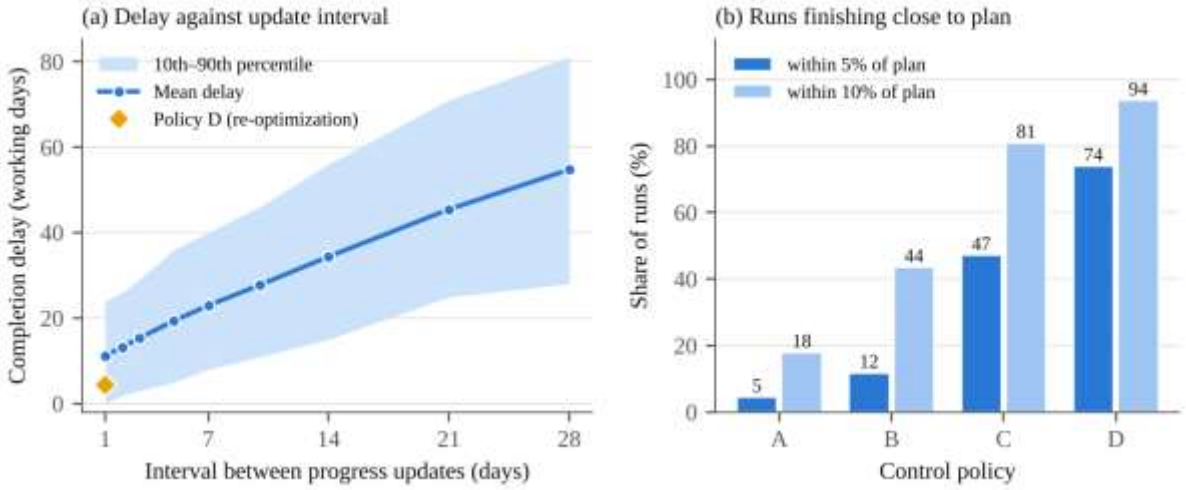


Fig. 7. (a) Mean completion delay against the interval between progress updates, with crew priority following the baseline sequence; the marker shows policy D. (b) Share of runs finishing within 5% and 10% of the planned duration.

E. Interpretation and limits of the experiment

Two mechanisms produce these results. Frequent synchronization shortens the time for which a hold remains unrecognised, which both starts its resolution sooner and releases the crew that was waiting on it. Re-optimization then directs crews and acceleration to the work that governs completion given the current state, which the baseline sequence no longer reflects once disturbances have occurred.

The size of the effect depends on the assumptions. It is sensitive to how often holds occur, to how long an unrecognised hold would in practice wait before someone acts, and to how much freedom there is to resequence work. The model assumes that progress is sensed without error, that a recovery plan is implemented on the day it is issued, and that all holds can be detected from data the twin receives. A real twin will fall short on each of these. The experiment also omits cost. The results should be read as an

argument for why the framework is worth testing, and as a specification of what a pilot study should measure.

V. IMPLEMENTATION IN THE SAUDI CONTEXT

A. Roadmap

Fig. 8 gives an indicative roadmap in five phases. The first establishes the data foundation: a common data environment, a 4D model, and a coding structure that links model elements to schedule activities. The second introduces automated capture on pilot zones and reaches the digital shadow level. The third adds forecasting and what-if simulation. The fourth closes the loop with re-optimization and an approval workflow. The fifth links the twins of separate packages so that dependencies across a programme are visible. The durations are indicative and overlap deliberately, since each phase can begin on pilot areas before the previous one is complete across the project.

B. Barriers and enablers

Table VIII relates the barriers reported in the Saudi literature to measures within the framework. The lack of standardisation, which ranked highest among challenges in the survey of Saudi professionals [15], is addressed by fixing the data schema and activity coding in the first phase and by adopting ISO 19650 information management [36]. Limited understanding of the technology and limited IT infrastructure [15] are addressed by phasing, so that value is shown on pilot zones before investment is extended. Awareness and leadership, identified as fundamental to BIM adoption in the Kingdom [34], point to the role of public owners in requiring the twin in their contracts.

C. Alignment with Vision 2030

Table IX maps the capabilities of the framework to the three themes of Vision 2030 [1]. The most direct contribution is to timely delivery of the projects on which the programme depends. The framework also supports the digital transformation of a major economic sector and gives public owners a more transparent basis for monitoring expenditure against progress.

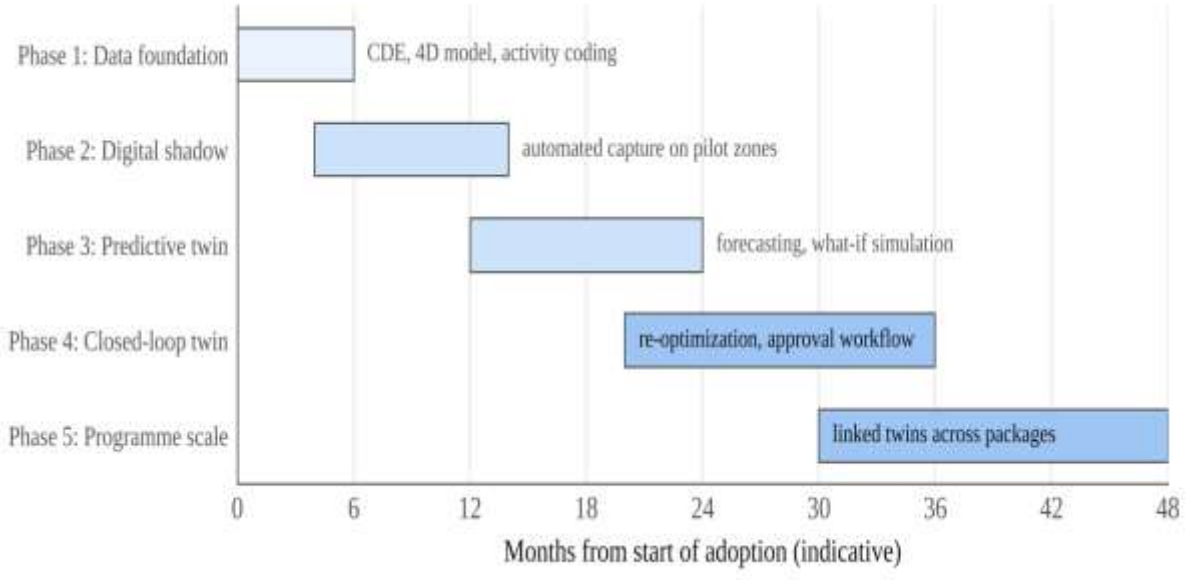


Fig. 8. Indicative implementation roadmap. CDE = common data environment.

TABLE VIII. REPORTED BARRIERS AND CORRESPONDING MEASURES IN THE FRAMEWORK

Barrier	Source	Measure in the framework
Lack of standardisation for integrated digital twin and AI	[15]	Common data schema and activity coding fixed in Phase 1; ISO 19650 information management
Limited understanding of AI capabilities	[15]	Explainable indicators (SPI(t), forecast slip); planner approval retained
Limited IT infrastructure and logistics	[15]	Phased deployment starting with pilot zones
BIM still relatively new; awareness and leadership needed	[34]	Owner requirement for 4D model and twin in contract documents
Fragmented implementation across life-cycle phases	[20]	Single twin model carried from planning through handover
Weak feedback from monitoring to scheduling	[12], [33]	Defined triggers, re-optimization step and approval workflow

TABLE IX. ALIGNMENT OF THE FRAMEWORK WITH VISION 2030

Vision 2030 theme	Relevant aim	Contribution of the framework
A thriving economy	Delivery of giga-projects and infrastructure; growth of a digital economy	Earlier detection of schedule deviation and faster recovery; local capability in construction technology
An ambitious nation	Effective, transparent government and efficient public spending	Auditable record of progress, holds and decisions for public owners
A vibrant society	Housing, public facilities and liveable cities available when planned	More reliable completion dates for housing and social infrastructure

VI. LIMITATIONS

The framework has not been applied to a live project. The simulation uses a synthetic project and assumed parameters, a single network structure, and a simple re-optimization heuristic, and it ignores sensing error, implementation delay and cost. The literature review that supports the framework was structured but was not a formal systematic review, and for some sources it relied on abstracts and bibliographic records. The megaproject figures in the introduction come from an industry study as reported in the press. Validation on a pilot project, with measured values for hold frequency, detection time and resolution time, is the necessary next step.

VII. CONCLUSION

This paper has proposed a digital twin framework that connects site sensing to schedule re-optimization for Saudi mega-projects. It specifies a five-layer architecture, a six-step operating cycle, indicators with

trigger thresholds, decision rights, and a re-optimization model in which candidate recovery plans are tested in the twin before one is issued. In an illustrative simulation of a synthetic project, shortening the progress update interval from fourteen days to one day reduced mean completion delay from 34.4 to 11.1 working days, and adding re-optimization reduced it to 4.3 days. These figures depend on the assumptions stated and are offered as a demonstration of the mechanism. Future work should calibrate the model with project data, test the framework on a pilot zone of a live project, extend the objective to include cost and carbon, and examine how linked twins can represent dependencies between the many packages of a giga-project.

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[Add acknowledgments here, or delete this section if there are none.]

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