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Research on Dynamic Control of Construction Schedule in Civil Engineering based on BIM Technology

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Abstract

Schedule overruns have been a problem for a long time in civil engineering projects, and the traditional, document-based management mode is no longer suitable for the uncertainties of modern construction sites. Building Information Modelling (BIM) provides a good path forward for moving schedule management from post-event reporting to continuous, model-driven control. Research has been conducted on how to incorporate BIM into all links of construction schedule management and build a closed-loop dynamic control system. Based on the above review of related studies, a three-tier structure has been proposed: a data layer, a model layer and an application layer; the 4D BIM model will serve as the information hub connecting the baseline schedule, field progress data and corrective decision-making. The first two enabling technologies are 4D construction simulation and multi-source progress data collection; the third is BIM-integrated earned value analysis and deviation-driven schedule re-optimisation. Then, the above framework will be applied to a high-rise office building project. According to the case study, after introducing BIM-based dynamic control, the schedule performance index increased from 0.82 in the third month to 1.00 at the end of the project; the frequency of progress coordination meetings dropped by about 40%, and the project was completed on schedule despite serious initial delays. Based on the above analysis, BIM can be employed to establish a closed-loop schedule control system; however, problems such as data standardisation, model granularity and organisational preparedness still need to be solved.

Keywords

Building Information Modelling (BIM); Civil Engineering; Construction Schedule; Dynamic Control; 4D Simulation; Earned Value Management.

1. Introduction

The three basic constraints of construction project management are time, cost and quality. However, according to the empirical data collected over many years, the actual results have been significantly worse than those expected from the management tools. Surveys in various countries have shown repeatedly that a considerable number of civil engineering projects are delayed, and these delays tend to spread: a slip in one trade or one floor is covered by buffers, appears further down the line, and is often discovered only after the recovery cost has risen substantially or become unfeasible. There are several structural reasons for the above situation. Construction production takes place in an open, changing environment; the supply chain is long and fragmented; and the information required to determine whether the project is progressing normally is distributed among drawings, bar charts, daily logs and the personal experience of site managers.

The old tool set for schedule management, Gantt charts, network diagrams and the critical path method (CPM), was developed in a time when information needed to be presented on paper. These tools are generally fixed. A first schedule will be drawn up before construction starts, printed out, and then updated manually at regular times based on reporting cycles rather than according to the actual progress of work at the site. Two defects arise directly. Firstly, the schedule is separate from the physical object it represents; activities in a bar chart do not have geometric or spatial attributes, so conflicts among trades, work areas and site logistics are usually found at the construction site rather than in the plan. Secondly, the speed and subjectivity of progress feedback are relatively low. Foremen typically estimate the percentage completed, engineers collect this data, and then during a weekly meeting, it is announced; by then, the information may already be outdated. Given the above circumstances, "control" will be reduced to post hoc explanations for deviations that have already occurred.

Building Information Modeling (BIM) has changed the technological premise of this problem. By integrating geometric information, component attributes and process information into a single object-oriented model, BIM makes it possible to connect the schedule to the building itself and to update that connection continuously. Since the concept was popularized in the early 2000s, BIM has moved from a design coordination tool toward a project delivery platform, and schedule management-often labeled 4D BIM when the time dimension is added—has become one of its most mature application areas. Azhar (2011) noted that BIM-based visualization and information integration can substantially improve the predictability of construction outcomes, while Bryde et al. (2013), reviewing thirty-five projects, identified schedule-related benefits as among the most frequently reported positive effects of BIM adoption. In China, large-scale infrastructure and building projects have likewise adopted BIM for schedule rehearsal and progress tracking, although the depth of application varies considerably (Cao et al., 2015).

Nevertheless, much of the current practice uses BIM in a one-off manner: a 4D model is built at the beginning of the project, demonstrated to the owner, and then gradually abandoned as the actual construction diverges from the original model. What is often missing is the feedback loop-the mechanism by which field data re-enter the model, deviations are quantified, and the plan is corrected in time. In other words, the value of BIM for schedule management lies not in producing a prettier plan, but in supporting dynamic control: a continuous cycle of planning, simulation, monitoring, comparison and adjustment.

Against this background, this paper addresses the following questions: (1) How can BIM be systematically embedded into the schedule management process so that a closed-loop dynamic control system can be formed?(2) Which technologies need to be realised in practice rather than just proposed theoretically? (3) What practical results can be achieved by applying this system to a real civil engineering project? Based on the above analysis, this paper first studies related research at home and abroad; then, it puts forward a BIM-based dynamic schedule control system, introduces the core technology of this system, and finally verifies its feasibility through a case study of a high-rise office building project. Finally, this paper presents the deficiencies and future research directions.

2. Literature Review

2.1 Construction Schedule Management and Its Deficiencies

Classical Schedule Management is based on CPM and its extensions. Find the critical path, calculate the float, and thus offer a feasible solution for compression and resource levelling. However, there are also deficiencies in construction practice that have been known for years. CPM schedules are generally prepared at a level of detail suitable for contract purposes, which is too coarse for daily production control; they assume relatively stable logic and duration, but the actual situation at the site is highly variable; and they do not provide direct information on space, so congestion and interference among crews are not visible until they occur. Lean construction researchers have criticised this "push" logic and proposed alternatives, such as the Last Planner System, where short-term commitments are made by those who actually carry out the work. Sacks et al. (2010a) have systematically studied the relationship between lean construction and BIM, and found that many lean concepts, such as reducing variation and improving flow, can be realised through BIM functions.

The Other Weak Link Is Progress Measurement. Traditional per cent-complete reports are subjective and infrequent. Therefore, many scholars have studied how to automate the process of progress observation. Golparvar-Fard et al. (2009) proposed the D4AR model to overlay 4D as-planned models onto time-lapse site pictures for visual and quantitative identification of deviations. Subsequently, this concept was expanded to include unordered daily photo collections registered against IFC-based models (Golparvar-Fard et al., 2015) and point-cloud-based geometric comparisons (Braun et al., 2015). According to the review by Ekanayake et al. (2021), reality-capture technology has advanced to the extent that regular, unbiased progress data can now be obtained through photogrammetry, laser scanning, RFID and IoT sensing; however, its connection with schedule systems is still lacking.

2.2 BIM and 4D Modelling for Schedule Management

Adding time as the fourth dimension to a 3D model is theoretically straightforward but difficult to implement in practice. Eastman and others (2011) have listed the requirements for such a model: an appropriate level of detail, a well-organised work breakdown structure, and reliable mapping rules between model components and schedule activities. Under the above circumstances, 4D simulation can be used to conduct virtual construction before actual implementation, identify spatial-temporal conflicts, and present the plan intuitively to subcontractors. Barlish and Sullivan (2012) conducted a case study to determine whether BIM could reduce the amount of schedule-related rework and coordination efforts. Succar (2009) put forward a staged BIM system at the strategy level to show how model-based collaboration will progress from object-oriented modelling to network-oriented integration, and this stage is exactly when dynamic schedule control can be realised.

Researchers have also studied the organisation of these. Eadie et al. (2013) conducted a survey on BIM application throughout the UK's construction cycle and found that although schedule-related applications were perceived as having a high benefit, they faced obstacles due to skill deficiencies and contract provisions. Chen et al. (2015) put forward an all-encompassing conceptual system for BIM and buildings, and pointed out that merely introducing new technologies will fail to achieve expected results unless changes are made to processes and institutions. Cao et al. (2015) have conducted empirical research in China on BIM practice and found that the impact of BIM on schedule control is significantly mediated by the support provided by project owners and the level of maturity of the implementation team; therefore, timely decisions require strong management commitment.

2.3 Dynamic Control and Research Gap

According to control theory, all good control systems need to have the following four parts: a reference (a plan), a sensor (to measure how far off it is), a comparator (to find out if there is a difference), and an actuator (to correct it). Map this structure to construction schedule management to see where the current BIM applications lack. Many of the reported applications cover the reference (4D baseline models) and, increasingly, the sensor (automated progress capture). The comparator and actuator stages quantify the deviation in schedule terms, diagnose the cause of this deviation, and feed back the correction to an updated model; these functions are relatively undeveloped and are often carried out outside the BIM environment. Pučko, Z. et al. (2018) Earned Value Management (EVM) provides a good foundation for comparison in terms of quantity, but traditional EVM focuses on cost accounts rather than model elements and thus has limited diagnostic accuracy. Therefore, combining EVM and BIM at the level of components and activities is a reasonable choice and remains an open problem for study.

In summary, the literature shows (i) mature knowledge of 4D modeling, (ii) rapidly maturing progress sensing, and (iii) a persistent gap in closed-loop integration. This paper targets exactly that gap by

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proposing a framework in which the BIM model functions as the persistent information hub through which the whole control cycle runs.

3. A BIM-Based Dynamic Schedule Control Framework

3.1 Overall Architecture

The proposed framework, illustrated in Figure 1, is organized into three layers connected by a feedback loop.

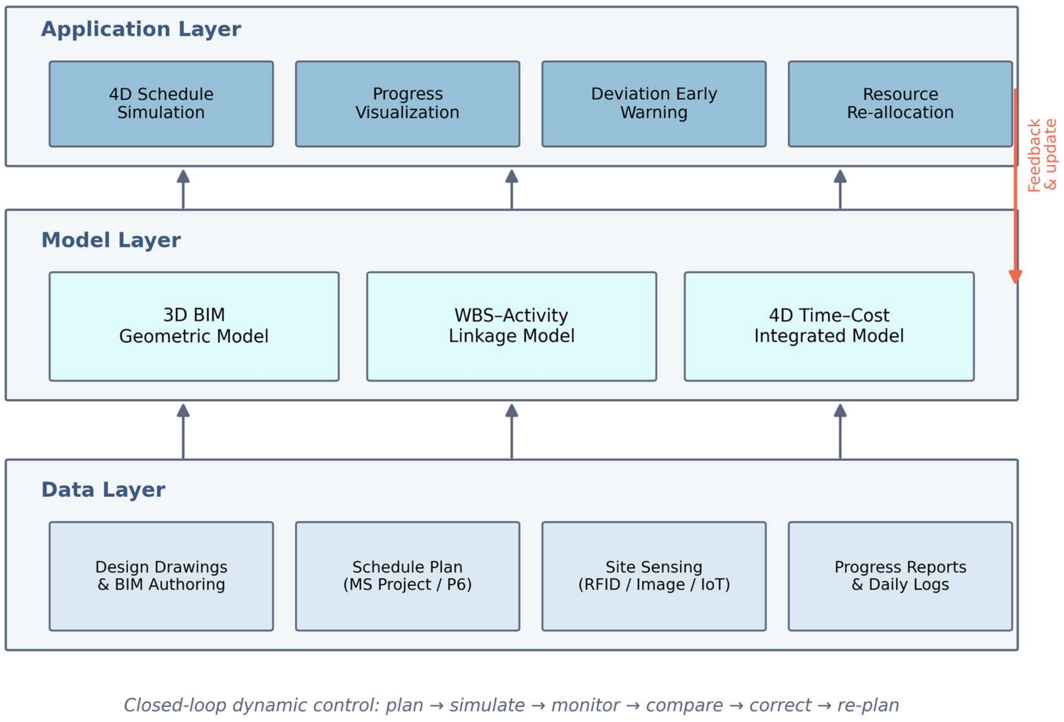

Figure 1. Overall framework of BIM-based dynamic schedule control

The **data layer** collects and standardizes all information required for schedule control. It includes design information (drawings and the authored BIM model), planning information (the baseline schedule prepared in tools such as MS Project or Primavera P6), and field information (daily logs, progress reports, and data captured by RFID tags, site cameras, photogrammetry or IoT sensors). At this level, we do not need a large amount of data; rather, it should have a good structure, and each item of progress information needs to be linked back to specific model parts and schedule activities.

The Model Layer is the centre of the system. Three sub-models are maintained and kept in line: the 3D geometric model, the WBS-activity linkage model, and the 4D time-cost integrated model. The link model needs to be introduced; otherwise, there will be no way to map the elements of the work breakdown structure (WBS), schedule activities and BIM components for control purposes. A rule of thumb used in this study is that the granularity of the model should correspond to the level of detail at which the site management team can realistically observe changes; otherwise, if too detailed and unable to obtain data promptly, it will be impractical.

The application layer provides the functions that project participants need to use: 4D simulation of the construction sequence, visualisation of as-built vs. as-planned state, automatic calculation of schedule deviation and early warning, and decision support for resource reallocation and schedule re-optimisation. As shown by the feedback arrow on the right of Figure 1, after the correction process, the resulting data will not be saved in a report; instead, it will return to the model level and serve as

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a new baseline for the next control cycle. Thus, the framework can implement the PDCA (Plan-Do-Check-Act) cycle in a model-based system.

3.2 Comparison with the Traditional Mode

Table 1 shows the comparison of the traditional document-based mode of schedule management with the BIM-based dynamic mode proposed in this study across six dimensions derived from the literature and interviews with practitioners in this research.

Table 1. Comparison of Traditional and BIM-Based Schedule Management

Dimension	Traditional document-based mode	BIM-based dynamic mode
Information carrier	2D drawings, bar charts, text reports	Integrate 3D/4D models as the single source of truth
Plan expression	Abstract Activity Bars; Implicit Spatial Relations	Visualise the construction sequence; find spatial-temporal conflicts early on
Progress data	Manual, subjective, weekly or infrequent	Multi-source, objective, daily or near-real-time
Deviation detection	Lagging; frequently occurs in coordination meetings	Automatic comparison at the component/activity level; threshold-based early warning
Corrective action	Based on experience, verbally or through revised printouts.	Model-based re-simulation of alternatives; updated plan shared via the model

The table should not be interpreted as saying that the old way is useless; CPM logic and the experience of planners are still required. In other words, BIM has changed the carrier for these assets and reduced the feedback loop from weeks to days; thus, even small errors can be corrected in time at a relatively low cost.3.3 The closed-loop control workflow

Figure 2 is the operating flowchart for the instantiation of the framework at the construction stage. Six steps form one control cycle, which is executed on a rolling basis-typically weekly for activity-level control and monthly for milestone-level control.

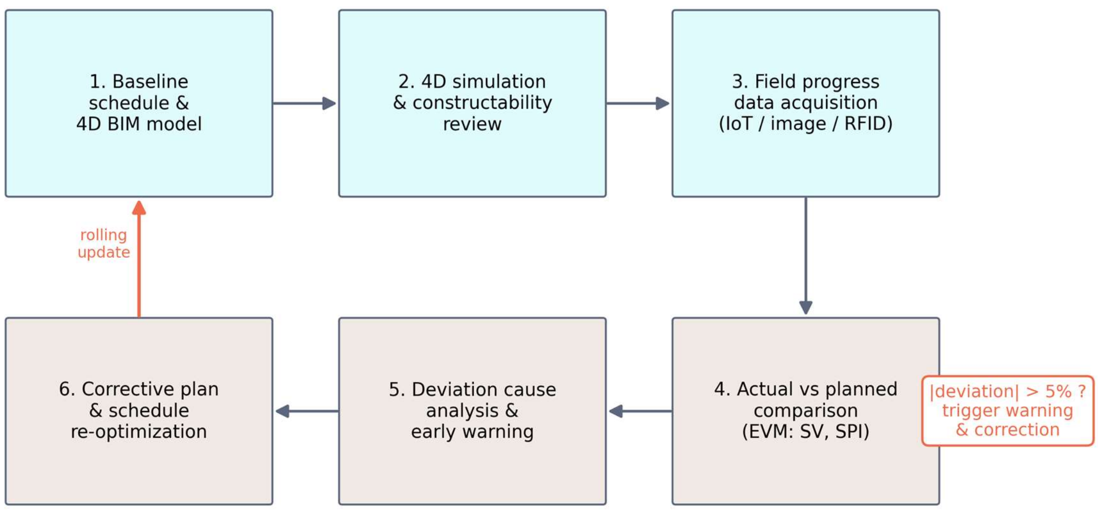

Figure 2. Closed-loop workflow of dynamic schedule control

In step 1, the baseline schedule is linked to the BIM model to form the 4D baseline. Step 2 rehearses the plan through simulation, allowing the team to resolve sequencing and workspace problems before mobilization. During execution (step 3), field data are acquired through the channels of the data layer and mapped onto model elements. Step 4 compares actual with planned states and computes schedule variances and performance indices. When a deviation exceeds a predefined threshold-set at 5% at the activity level in the case study reported below-the early-warning mechanism is triggered and step 5 initiates a cause analysis that distinguishes between productivity problems, supply problems, design changes and external events. Step 6 formulates corrective measures, evaluates them through re-simulation, and issues an updated schedule, which becomes the reference for the next cycle. The decisive property of this workflow is that every step manipulates the same model, so information losses between the stages of the control loop are minimized.

4. Key Technologies

4.1 4D Modeling and Construction Simulation

The quality of dynamic control is bounded by the quality of the 4D model. Three modeling issues proved critical in this research. First, granularity alignment: Structural components such as columns and slabs can generally be mapped directly to activities, but finishes and MEP work often require temporary aggregation or subdivision of model elements to align with the WBS. Second, there is a lack of geometric representation for procurement, approval and curing activities; although they do not have a physical form in the model, they are part of the critical path and have been added as attribute sets to the corresponding zones. Thirdly, there is a workspace model. Temporary facilities, tower crane coverage and material staging areas were explicitly modelled because a large proportion of schedule conflicts arise from space issues rather than logical ones. Then, at the beginning of the simulation and after each correction plan, it was also run to check whether there would be any adverse effects of accelerating measures, such as adding a crew to a crowded area, before actually implementing them.

4.2 Multi-source Progress Data Collection

No single sensing technology can cover all kinds of work, so a practical combination is used in the framework. Photogrammetry was conducted weekly at fixed points and drones were flown to collect geometric data on the constructed parts; then, based on the method presented by Golparvar-Fard et al. (2015), image-based reconstruction was registered against the IFC model. Prefabricated components and large batches of materials were tagged with RFID chips for discrete status updates (production, delivery, installation). For the repetitive interior works where automated recognition is still unreliable, foremen reported completion by scanning QR codes on the zone board; this deliberately low-tech method turned out to be more reliable than advanced ones. All channels write to a common progress database indexed by model element GUIDs, and this is how the automatic comparison in the next step is performed. This hybrid mode is in line with the findings of Ekanayake et al. (2021); thus, the goal is timely and reliable data rather than high-end technology.

4.3 BIM-integrated Earned Value Analysis

Earned Value Management provides the quantitative reference for the control loop. In the traditional arrangement, EV metrics are calculated based on cost accounts that combine many physical components, so a negative schedule variance shows that the project is late but does not specify where. In the proposed framework, budgeted costs and planned dates are linked to model elements via a linkage model, and thus PV, EV and AC can be calculated at the level of a zone, a floor or even a single activity chain. Then, automatically calculate the Schedule Performance Index ($SPI = EV/PV$) and Schedule Variance ($SV = EV - PV$) for each control period and each branch of the WBS. Deviation patterns are now clearly visible; they show systematic slippage in one trade rather than scattered noise and have improved the quality of cause analysis in Step 5 of the workflow. It should be noted that EVM has some deficiencies, such as the tendency for SPI to approach 1 near the end of

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the project regardless of whether it is late; therefore, the system still uses milestone-based absolute checks along with the indices.

4.4 Deviation-driven Schedule Re-optimisation

When a warning occurs, the planner needs to solve a constrained re-optimisation problem to recover the milestone dates with minimal extra cost and risk under logic, resource and workspace constraints. The framework provides the following three types of support. First, the link model can determine which downstream activities are affected by a particular deviation without manual tracing. Second, alternative correction scenarios, such as re-sequencing, crew expansion, extended shifts, and parallelisation of originally sequential work, are encoded as candidate modifications and evaluated via 4D re-simulation to uncover spatial side effects that pure network re-computation fails to show. Third, the selected scenario is released as a new baseline version, and version control will be used to keep track of the history of baselines and the reasons for any changes. The final reason is that a written record of the starting point, deviation, cause and response can serve as proof in a delay claim or dispute.

5. Case Study

5.1 Project Overview and Implementation Setup

A high-rise office building project in a large city in eastern China was used as the case study. The main contents of Table 2 are shown below. Given that the project had a short construction period and a relatively high trade density in the podium area and typical floors, dynamic control was required here.

Table 2. Overview of the case project

Item	Description
Building type	High-rise office building with a 4-storey podium
Structure	Frame–core tube, cast-in-situ reinforced concrete
Gross floor area	Approx. 86,000 m² (28 storeys above grade, 3 basement levels)
Contract duration	730 calendar days for the main contract scope
BIM software environment	Revit (authoring), Navisworks (4D simulation), MS Project (scheduling), self-developed progress data platform
Control cycle	Weekly at activity level; monthly at milestone level
Warning threshold	Activity-level deviation > 5% or SPI < 0.90 for two consecutive periods

A BIM implementation plan was released prior to construction, specifying the level of detail (LOD 300 for structural components, zone-level aggregation for finishes), the WBS-element mapping rules, the data acquisition paths mentioned in Section 4.2, and the responsibility for model maintenance. Two engineers were appointed as model coordinators, and instead of general software courses, the site management team received short, task-oriented training that was very useful for acceptance.

5.2 Monitoring Results and Deviation Evolution

Table 3 shows the monthly cumulative planned value (PV), earned value (EV) and the resulting schedule performance indicators over the twelve-month principal monitoring period for both the superstructure and the main fit-out stage. The same data are shown as earned value S-curves in Figure 3, and Figure 4 plots the monthly SPI against the warning threshold.

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Table 3. Monthly Progress Monitoring Data for the Case Project

Month	PV (cum. %)	EV (cum. %)	SV (%)	SPI	Status
1	8.0	7.0	−1.0	0.875	Watch
2	16.0	13.5	−2.5	0.844	Warning
3	25.0	20.5	−4.5	0.820	Warning
4	34.0	29.0	−5.0	0.853	Correction launched
5	43.0	38.0	−5.0	0.884	Recovering
6	52.0	47.0	−5.0	0.904	Recovering
7	61.0	56.5	−4.5	0.926	Recovering
8	69.0	65.5	−3.5	0.949	Recovering
9	77.0	74.0	−3.0	0.961	Watch
10	85.0	82.5	−2.5	0.971	Watch
11	93.0	91.5	−1.5	0.984	Normal
12	100.0	100.0	0.0	1.000	On time

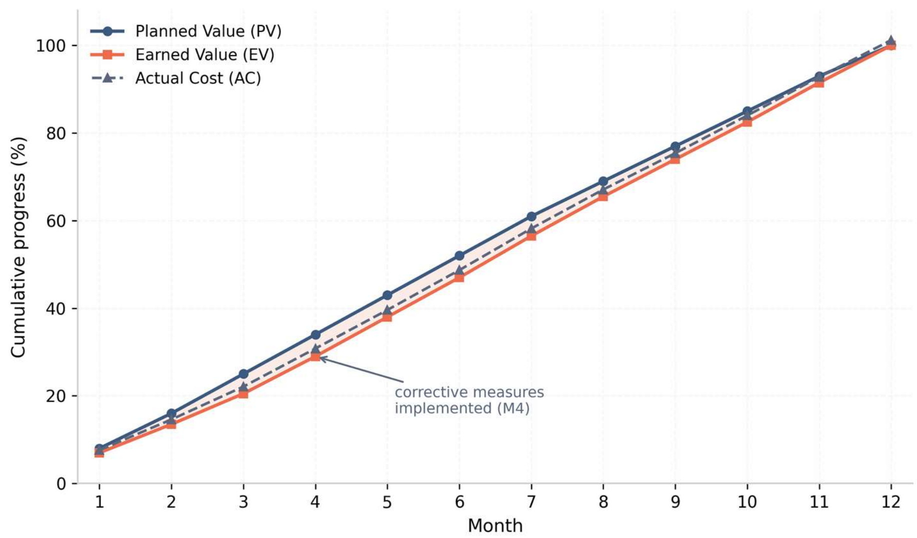

Figure 3. Earned value S-curves of the case project

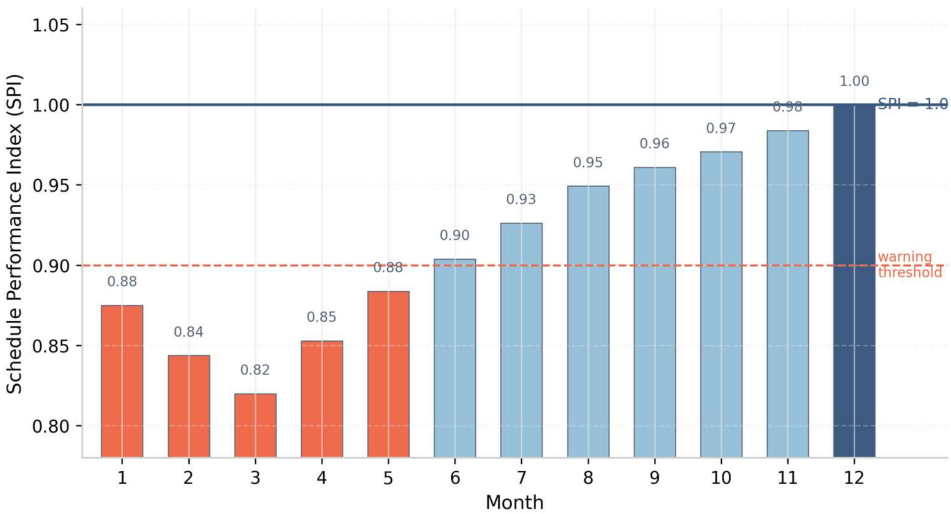

Figure 4. Monthly Schedule Performance Index and Warning Threshold

The Data Show a Consistent Trend. In the first three months, the project was behind schedule, and by the end of month 3, the SPI had dropped to 0.82. Based on the component-level EV decomposition, the two reasons for the delay were identified as follows: First, due to a regional supply shortage, the delivery of reinforcement steel was delayed; Second, the productivity of the formwork crew working on the irregular podium floors was lower than expected. Both causes had been shown in the weekly activity-level data several weeks before they appeared in the monthly summary; thus, they served as an early warning signal for the site team and were considered the most important features of the system.

From Month 4, correctives were taken according to the workflow shown in Figure 2. The podium sequence was re-planned via 4D re-simulation, and some of the original sequential formwork cycles were converted into two parallel zones; a second reinforcement supplier was qualified; and an extra crew was added to the critical tower-zone cycle after simulation confirmed that workspace congestion would remain within acceptable limits. As shown in Table 3, the cumulative schedule variance did not increase further beyond -5.0% and gradually decreased; by the sixth month, SPI had exceeded 0.90, and at the end, it reached 1.00. The project will be completed by the agreed-upon time. As shown in Figure 3, the actual cost curve has risen slightly due to the acceleration measures; this increase is relatively small at around 1.2% and was expected based on the simulated scenarios.

5.3 Auxiliary Observations

Some other types of changes have also been observed. The weekly coordination meeting has been reduced from around 100 minutes on average to about 60 minutes, as the discussion now starts with an agreed-upon visual model of deviations rather than with conflicting verbal reports; over the course of the monitoring period, this has resulted in a saving of about 40% of meeting time. Requests for information about sequencing and workspace dropped significantly after the 4D rehearsal sessions. Perhaps most notably, the site team voluntarily continued to update the model after the official research period had ended; based on their own experience, the authors believe that such behaviour indicates that the system is considered useful by its users rather than being viewed as an inconvenience.

6. Discussion

Based on the above cases, it can be concluded that BIM serves as the foundation for a closed-loop dynamic schedule control system, and when applied in this way, measurable results such as early identification of deviations, quantified recovery, and timely delivery align with the advantages shown in previous research (Bryde et al., 2013; Barlish and Sullivan, 2012). Nevertheless, the three points also need to be addressed.

Firstly, the contribution of BIM should not be exaggerated. The recovery shown in the case study was achieved through managerial decisions, such as re-sequencing, re-supply and re-staffing; these could have been carried out without BIM. The model-based system modified when and how these decisions were made: about three to five weeks before the time when they would have been reported in the old way, and the scope of correction was explicitly limited by space and logic. Dynamic Control can be regarded as both a result and a model for an information system.

Second, there are actual implementation costs and barriers. Construction and operation of the link model required continuous work, and the hybrid data collection method also needed to be managed by foremen and suppliers. Based on the above research, Eadie et al. (2013) and Cao et al. (2015) have found that skills, standardised processes and management commitment affect the benefits of software more than its features. Therefore, this framework is more suitable for medium- to large-scale projects where the fixed cost of the system can be spread over a long and complex construction period.

Third, some deficiencies in this study will be addressed in the future. The evidence is based on a single case, and although the monitoring data have been organised, they were partially obtained through manual collection methods that lack the objectivity of automated collection. Set up the

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warning limits reasonably, and then adjust them for different kinds of projects. Finally, the re-optimisation step is currently a decision-support system rather than automatic optimisation; coupling the framework with formal scheduling optimisation algorithms and new digital-twin infrastructure will be explored in the future.

7. Conclusion

This paper set out to investigate how BIM technology can support the dynamic control of construction schedules in civil engineering. Its main contributions and findings are as follows.

A three-layer framework-data layer, model layer and application layer-was proposed, in which the 4D BIM model acts as the persistent information hub of a closed control loop covering planning, simulation, monitoring, comparison, correction and re-planning. The framework makes explicit the feedback path that is missing in many one-off 4D applications.

Four enabling technologies were identified and integrated: granularity-aligned 4D modeling with explicit workspace representation; hybrid multi-source progress data acquisition keyed to model elements; BIM-integrated earned value analysis that localizes deviations at component and activity level; and deviation-driven re-optimization supported by 4D re-simulation and baseline version control.

Application to a high-rise office building project demonstrated the operability of the framework. The schedule performance index recovered from 0.82 to 1.00, deviations were detected several weeks earlier than under the traditional reporting chain, coordination meeting time was reduced by about 40%, and the project was delivered on the contractual date with a modest, consciously accepted cost premium of about 1.2%.

In short, the application of BIM to schedule management has been realised not by creating a single 4D model but through the continuous operation of a model-based control loop. In the future, research will expand this framework to include automatic schedule optimisation, deeper integration with digital twin platforms, and multi-project empirical verification.

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