

Empirical Validation of Predictive Project Controls for Early Schedule-Risk Detection: Analysis of CPM Float Erosion and Milestone Performance in Construction Projects

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Abstract

Construction projects involve early detection of schedule degeneration before milestones failure can be detected. This paper measures predictive project controls using the secondary quantitative longitudinal analysis of the historical Critical Path Method schedule data. It discusses the monitors of early-warning measures by Float Erosion Rate, Float Runway, Runway Ratio, and schedule-performance indicators. Primavera P6 updates has been archived to evaluate the deterioration of milestones, warning lead time, false positives and false negatives. The study aims to substantiate whether longitudinal schedule, patterns give accurate and timely risk indication evidence of exposure of developing risk to reinforce previous research, making of informed decisions and successful intervention in construction project management.

Keywords: Project Controls, Predictive Scheduling, Schedule Risk, CPM, Float Erosion.

I. Introduction

Construction Schedule Control and Milestone Performance

Effective schedule management is critical towards offering construction projects on schedule and safeguarding critical contractual and operation milestones. Critical Path Method schedules give details of activity sequencing, float and remaining durations and projection of dates [1]. The tracking of these variables can be used by project teams to evaluate the level of performance and detect new constraints emerging as well as assist in timely management decision-making during the execution of the projects [2].

Limitations of Reactive Project Controls

The conventional project controls focus in measuring the current performance and reporting approved baselines and variances. Whereas this is necessary, before the traditional indicators could show milestone influence, schedule deterioration can be developed [3]. Slippage in the activity of repeated activities, shorter and shorter remaining durations, and amended forecast dates can continuously diminish schedule resilience with a milestone still seeming possible in the remaining programme.

Predictive Project Controls and CPM Trends

Predictive project controls build on the traditional reporting basis by analyzing the schedule conditions variation over periods of reporting [4]. Longitudinal

CPM analysis can disclose the patterns that can be missed by isolated updates [5]. The trend in float erosion, change in remaining-duration, forecast movement, procurement-dates, near-critical paths and performance indicator can give early warning signs such that a milestone is becoming progressively subject to exposure to schedule risk.

Research Problem and Study Approach

The focal issue of the research is whether trends of CPM of the past can be trusted as warning of the risk of milestones schedule [6]. The risk of failure can be detected in time. This paper explores the research question on whether longitudinal CPM schedule indicators can be empirically reliable early-warning signs of milestone schedule risk via secondary quantitative analysis of past construction project data, without interviews, thematic analysis, or qualitative coding.

Research Aim

This study seeks to perform empirical research assessing the effectiveness of longitudinal CPM schedule indicators in the early identification of milestone schedule risk on construction projects by secondary analysis of historical project-control data.

Research Objectives

- *To investigate CPM schedule trends over a period of time as a way of establishing float erosion trends, and the occurrence of schedule risk in construction projects.*

- To determine Float Erosion rate, Float runway and Runway ratio as early-warning indicators of Milestone performance.
- To determine how schedule-performance indicators relate to deterioration in milestones subsequently with secondary quantitative data.
- To establish the performance of predictive project controls to produce warning of milestone schedule risk in a timely manner.

Research Contribution

The study adds to the body of project control research by an empirical assessment of longitudinal trends of CPM as to whether it can be used to enable the earlier recognition of milestone timing risk. It evaluates the speed at which it happens, such as Float Erosion Rate, Float Runway and Runway Ratio as leading indicators with the help of secondary quantitative data, which gives evidence in favor of predictive scheduling practices and enhances timely decision making in the framework of construction project management.

II. Background And Rationale From Reactive to Predictive Project Controls

Reactive project controls report the circumstances of status and uncertainties of approved schedules, whereas predictive controls aim at identifying signs of vulnerability before milestones are affected [7]. Cross-linking of schedule information between reporting periods can help teams to identify patterns of deterioration at an earlier stage [8]. This change of emphasis moves away what has already happened to what is transforming and where the management investigation might be needed.

Beyond the Current Critical Path

Concentrating on the existing critical path will not consider activities and paths that are about to become critical. Near-critical paths are capable of eating schedule before getting their critical label because of recurring loss of float [9]. The observing of changes in float, remaining duration, logic, forecast dates, constraints and the downstream relationship may therefore give an indication of emerging exposure whilst an opportunity of investigation and corrective action still exists [10].

Float-Based Early-Warning Indicators

There are three indicators of the screening of the framework. Float Erosion Rate Calculates average float that is lost per reporting period [11]. Float Runway calculates the amount of potential current float which might be consumed in the event that current erosion persisted. Runway Ratio is a comparison of Float Runway and remaining runway length, which knows milestones where the estimated schedule resilience is less than the amount of work that remains [12].

The corresponding measures are:

$$FER = \frac{TF_{k,t-n} - TF_{k,t}}{n}$$

- FER = Float Erosion Rate
- TF = Total Float
- k = Milestone
- t = Current reporting period
- n = Number of periods analyzed

$$R_f = \frac{TF_{k,t}}{FER}$$

- R_f = Float Runway
- TF = Total Float
- FER = Float Erosion Rate

$$\alpha = \frac{R_f}{RD_k}$$

- α = Runway Ratio
- R_f = Float Runway
- RD = Remaining Duration

Rationale for Empirical Validation

The indicators are designed as screening mechanisms as opposed to deterministic forecasts of milestone failure. They can be influenced by schedule logic, calendar, constraints, progress being updated, assumptions of remaining-duration, and execution change [13]. Thus, the thresholds proposed should not be regarded as standards. The data used in the historical project should be analyzed to test the predictive usefulness, lead time to warn, and performance in category.

III. Related Work Historical CPM Schedule Trends, Float Erosion, and Emerging Risk in Construction Projects

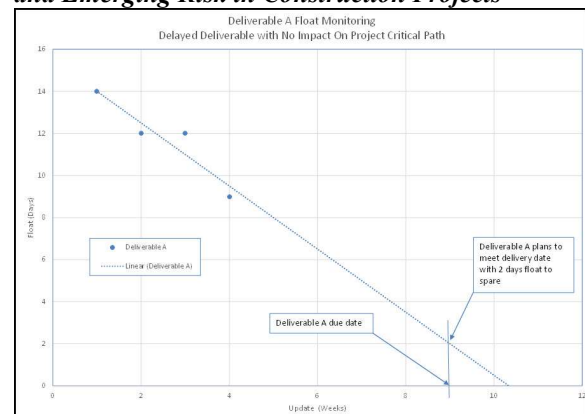


Fig 1. Longitudinal CPM Schedule Trends and Float Erosion in Construction Projects

The concept of CPM research has a long tradition of focusing on criticality and float status at any point in time, but independent updates to the schedule can mask a gradual decline. Longitudinal analysis is more diagnostic as the float erosion as well as the duration increase and path convergence are revealed [14]. It can

be seen that float variations could be caused by logic modification, calendar alteration, constraint modification, or sequencing modification and not due to a decrease in performance [15]. The old CPM trends, then, should be thoroughly verified before interpreted as reliable pointers of looming construction risk scenario.

Evaluating Float Erosion Rate, Float Runway, and Runway Ratio for Milestone Performance



Fig 2. Float Erosion Rate, Float Runway, and Runway Ratio Early-Warning Framework

The Float Erosion Rate, Float Runway, and Runway Ratio are the organized ways of converting the decreasing flexibility of schedules into possible early warning events. This makes them easy to use in practice, but places some methodological constraints. Float Runway is based on the assumption that recent erosion is linear, whereas Runway Ratio finds too much risk when a significant amount of work still remains [16]. That is why, put forward thresholds must be empirically tested on completed projects in order to be confident about their predictive performance on milestones.

Schedule Performance Indicators and Their Relationship with Subsequent Construction Milestone Deterioration Patterns

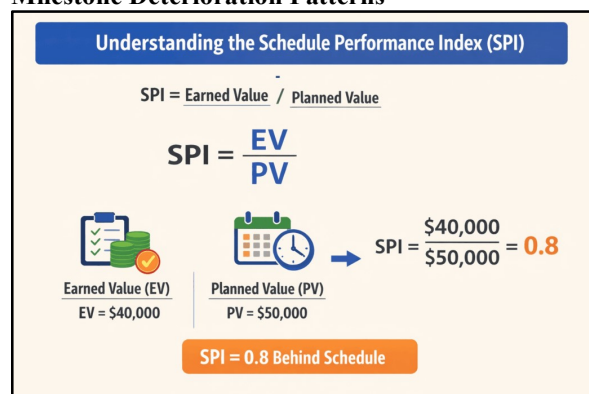


Fig 3. Integrated Schedule Performance Indicators and Milestone Deterioration

Schedule-performance indicators are helpful evidences of project decay, though each of the measures might not be a sufficient indicator of risk on milestones. An example is SPI, which is relative to

earned-value performance even without determining whether a delayed work is delayed on the critical path [17]. Exceptional performance degradation, coupled with abetting float, increasing time span, floating purchase motion, and forecast slippage might provide more diagnostic indicators [18]. Still, the overall effectiveness of combined indicators over single measures is an empirical issue that has not yet been resolved satisfactorily, and it is necessary to conduct systematic secondary analyzes of datasets of projects of different eras so as to be able to draw conclusions about their superiority or inferiority.

Effectiveness of Predictive Project Controls for Timely Warning of Milestone Schedule Risk

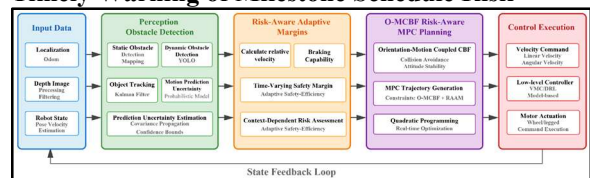


Fig 4. Predictive Project Controls Framework for Early Milestone Risk Detection

The predictive project controls may expand traditional reporting, spotting the worsening situation ahead of the milestone impact, who have more time to intervene the situation. Yet, the effectiveness of early-warnings is conditional on quality of schedules, quality of reliable updates, relevant thresholds and proper interpretation of converging signs [19]. Current conceptual arguments cannot stand alone to create predictive reliability [20]. Thus, the efficacy ought to be measured by back testing the history on the basis of warning lead time, false positives, false negatives, complexity of the project, and future milestones and measure them empirically.

Research Gap

The current literature only gives conceptual early-warning measures without empirical validation with historical construction schedule data, whereas the float behavior can be misleading due to changes in logic, constraints, and historical forecasting assumptions. To overcome these weaknesses, this study involves secondary quantitative research, experimenting on CPM trends, Float Erosion Rate, Float Runway and Runway Ratio in relation to milestone results, in determining their predictive utility and their application efficacy.

IV. Methodology

Research Philosophy and Approach

The paper uses a post-positivist quantitative methodology as it analyzes quantifiable relations between historical selection indicators and future milestone results. The methodology acknowledges that schedule data can be observed yet the results are subject to modelling decision and project

circumstances. In reference to this, empirical testing of hypotheses related to float erosion and milestone deterioration can be used instead of them being possibly explained by qualitative accounts.

Research Design

A secondary quantitative longitudinal design is used. Schedule updates is archived on several reporting periods and is analyzed in a consecutive manner that changes can be studied as opposed to evaluating each update separately. The milestone of each reporting period can be the unit of analysis. There are no interviews, questionnaires, focus groups, thematic analysis, and qualitative coding.

Secondary Data and Sampling

Archived CPM or Primavera P6 schedule updates of finished construction projects and milestone records can make up the secondary data. The project eligible should include a successive update, distinguishable milestones, regular reporting dates, and adequate information about the schedule to compute trend indicators. Unfinished records of projects or periods where the quality of the schedule is not appropriate cannot be included. The ultimate sample size can thus be based on the available records and not a specified target.

Variables and Data Extraction

The variables to be extracted are activity ID, WBS, activity status, total float, free float, remaining duration, early finish, late finish, baseline finish, actual start, actual finish, constraints and data date. Each variable, measurement unit and analytical role can be defined in Table 1. Dependent variable can be subsequent deterioration or failure of milestones based on operational final definition.

Float Erosion Rate is:

$$FER_{k,t} = (TF_{k,t-n} - TF_{k,t})/n$$

where TF denotes minimum total float, k the milestone, t the current update, and n the reporting-period window.

Float Runway is:

$$R_{f,k,t} = TF_{k,t}/FER_{k,t}$$

where R_f denotes estimated reporting periods before available float is consumed if recent erosion continues.

Runway Ratio is:

$$\alpha_{k,t} = R_{f,k,t}/RD_{k,t}$$

where RD denotes remaining driving-path duration expressed in reporting periods.

Table 1. Variables, Measures, And Operational Definitions

Variable	Measure	Operational Definition
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Total Float (TF)	Days	Available schedule flexibility
Free Float (FF)	Days	Delay without affecting successor
Remaining Duration (RD)	Days/periods	Time required to complete remaining work
Float Erosion Rate (FER)	Days/period	Average float lost per reporting period
Float Runway (Rf)	Periods	Estimated periods before float exhaustion
Runway Ratio (α)	Ratio	Float runway relative to remaining duration
Forecast-Date Movement	Days	Change in forecast milestone date
Schedule Performance	SPI	Schedule performance against plan
Milestone Outcome	Binary	Deteriorated/failed or not
Warning Lead Time	Periods	Time from first warning to milestone impact

Quantitative Analysis

The first form of analysis will be descriptive statistics and longitudinal trends analysis. Associations between schedule indicators will be measured with the help of correlation and appropriate group comparisons. Regression or classification-based analysis will also test the hypothesis that FER, Float Runway, Runway Ratio, and schedule-performance are predictors of future milestone deterioration depending on the characteristics of the data and adequacy of sample used [21]. The predictive usefulness will be evaluated with false-positive rates, false-negative rates and warning lead time:

$$LeadTime = t_{impact} - t_{first\ warning}$$

These measures will establish both classification performance and practical warning value.

Reliability, Validity, and Schedule Quality

Trend interpretation is evaluated using schedule quality. They can focus on the erroneous progress updates, impractical remaining durations, over-constrained schedule, poor logic, out of date

association, and material logic adjustments or calendar changes. Sensitivity tests can investigate how the warning signals identified are consistent with problematic observations being removed [22]. The process can enhance dependability and can minimize the chances of identifying schedule-model changes as actual deteriorations in actual performance [23].

Research Flowchart

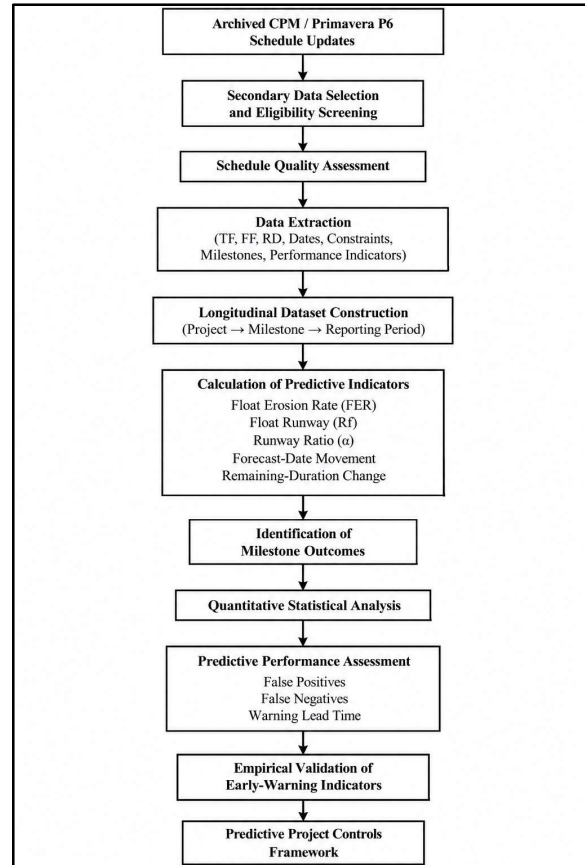


Fig 5. Secondary Quantitative Longitudinal Research Process

The number describes the longitudinal secondary-data approach used to assess the CPM-based early-warning signals, starting with historically-based schedule selection and quality control moving to compute the indicators, statistical calculation, and empirical validation of the indicators.

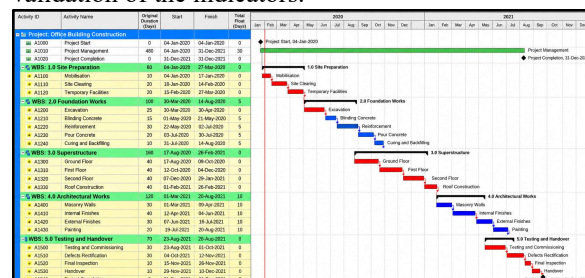


Fig 6. Primavera P6 Schedule/Gantt Showing Critical and Near-Critical Paths

The following figure demonstrates the weaknesses of the proposed secondary quantitative analysis to be operationalized with the help of longitudinal Primavera P6 schedule data. The activities are common construction phases, such as site preparation, foundation, superstructure, architectural works, testing, commissioning, defect correction, inspection and commission to a final project completion milestone [24]. The figure differentiates between critical, near-critical and non-critical activities and allows schedule exposure to be checked outside the existing critical path, which is in line with the predictive project-controls view of the study.

The order of activities is what eliciting the variables needed by the methodology is based on. Start and finish dates, activity status, constraints, and milestone relationships may be recorded, as well as, the remaining duration, for every reporting update. Updates in archives are then then combined longitudinally to enable the measurement of changes across successive periods of reporting and not the evaluation of the schedule as a one-time picture [25]. The near-critical path can be exemplified by the foundation activities. In the case reinforcement, concrete, and backfilling slowly lose their floating as updates occur, the route might become more and more capable of influencing the follow-up superstructure operations. On the other hand, the testing or handover activities and superstructure can be used to demonstrate a critical path in which there is scanty or no float, which implies that the project completion can be directly affected by the deterioration.

For each milestone k , the historical total-float values are used to calculate Float Erosion Rate (FER):

$$FER_{k,t} = \frac{TF_{k,t-n} - TF_{k,t}}{n}$$

Where TF represents total float and n represents the reporting-period window. Float Runway is subsequently calculated as

$$R_f = TF / FER$$

Using the Runway Ratio, it can be comparing Runway Ratio with the remainder of the driving path. The measures can convert the information on the schedules that the above figure represents into quantitative early-warning variables.

V. Illustrative Application, Expected Findings And Research Contribution

Illustrative Application of the Early-Warning Framework

In order to illustrate the way, the suggested indicators are going to be used in the data on the secondary schedule, the hypothetical commissioning milestone shown in the figure below is taken into account. Total float gradually decreased through the six reporting periods of 120, 96, 71, 48 and 21 days to -12 days.

Though the milestone maintains positive float till Month 5, the consistent decrease in it means the decreasing resilience of the schedule before negative float will be shown. This example thus demonstrates the importance of studying longitudinal CPM behavior as opposed to depending solely on the present schedule status.

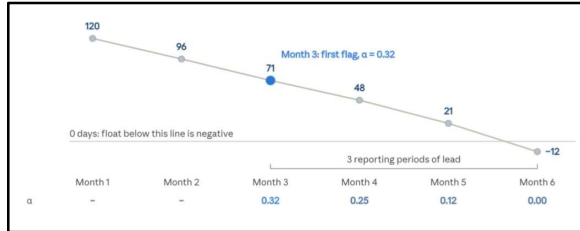


Fig 7. Illustrative Float-Erosion Trend and Early-Warning Point Before Negative Float

The framework will not be able to generate its first FER-based warning until Month 3 as the calculation adopted would need two periods of reporting historical float information [26]. The total float in Month 3 has decreased to 71 days.

The Float Erosion Rate hence:

$$FER = \frac{TF_{t-2} - TF_t}{2}$$

$$FER = \frac{120 - 71}{2} = 24.5 \text{ days/reporting period}$$

Thus, the milestone has consumed float at an average rate of 24.5 days per reporting period over the observed window.

Float Runway is subsequently calculated as:

$$R_f = \frac{TF_t}{FER}$$

$$R_f = \frac{71}{24.5} \approx 2.9 \text{ reporting periods}$$

This implies that, under the conditions that the recent rate of erosion persist unaltered, the remaining 71 days of float would hypothetically be exhausted in about 2.9 reporting periods. Notably, Rf is a linear screening-calculation, not an actual determination of how soon failure will happen.

At Month 3, the driving path contains nine reporting periods of remaining work. Therefore:

$$\alpha = \frac{R_f}{RD_k}$$

$$\alpha = \frac{2.9}{9} \approx 0.32$$

The resulting Runway Ratio of 0.32 is substantially below the illustrative threshold of 1.0. Under the proposed framework, this represents elevated exposure requiring investigation rather than confirmation that milestone failure will occur.

Table 2. Interpretation Of The Longitudinal Trend

Reporting Period	Total Float (days)	Runway Ratio (α)	Interpretation
Month 1	120	—	Insufficient history
Month 2	96	—	Insufficient history
Month 3	71	0.32	First warning
Month 4	48	0.25	Exposure increasing
Month 5	21	0.12	Severe exposure
Month 6	-12	0.00	Negative float

The figure shows the difference between early warning and traditional detection of negative float. Month 3 milestone still has 71 days of positive float but 0.32 depicts a lot of schedule exposure. Float then drops to 48 days and 21 days and then at Month 6, is broken to -12 days. Thus, the illustrative framework produces the initial warning three reporting periods prior to the negative float occurs.

An indicative decline in SPI of 0.98 to 0.84 in the six periods is also reported in the source. This adds to the multi-indicator method of the study: float erosion cannot be observed alone when other evidence of schedule-performance is present. Declining float, raising remaining durations, prediction movement, procurement changes and worsening performance indicators could prove to be better evidence than a single measure [27].

Management Interpretation of an Early Warning
Month 3 warning would be considered an investigation and not a failure of the milestone. The project-controls team would scrutinize real versus schemed advancements, lingering-duration assumption, predecessor logic, successor logic, change in constraints, move of procurement, alteration in the design or scope, resource supply, productivity suppositions, risk eventualities and past recovery endeavors [28].

The analytical process therefore follows five stages:

*Detect → Diagnose → Forecast → Act
→ Verify*

The detection determines the presence of material deterioration, diagnosis determines its cause, forecasting determines the result of possible

milestones, action decides what to do, resequencing, resources or procurement decisions join detection, and verification determines that later schedule adjustments show whether an intervention has rebuilt schedule resilience.

Expected Empirical Findings

Secondary quantitative analysis will allow identifying whether similar patterns as in the above figure are present in real histories of construction schedules. In particular, the research will examine the hypothesis that FER, Float Runway and Runway Ratio are reliable predictors of milestone erosion and whether a combination of these measurements with schedule-performance indices enhances their effectiveness in early-warning.

The evaluation of predictive performance will be based on the false-positive and false-negative, the warning new lead-time, sensitivity to schedule complexity, indicator relationships and indicator effects and the performance of combined indicators as compared to single indicators.

The three-period warning that is presented in the figure above should not be reported as an anticipated empirical finding. The source attached in particular warns that this lead time is an artifact of the data set of hypotheses and is not an indication that actual construction projects will fulfill the same warning period.

VI. Limitations And Ethical Considerations

The experiment relies on secondary history schedule information, the accuracy of which can be influenced by faulty progress warnings, unreasonable remaining schedule, logic modifications, constraints, calendar, and reschedule. The continued erosion is also the assumption of Float Runway, though the real trends may become faster, slower or better with the corrective action. As a result, during interpretation, there will be schedule-quality checks, whereas false positives and negatives will be addressed during validation [29]. Anonymization, safe handling, and use of project and organizational information will only be done with appropriate permission. The secondary quantitative analysis will be conducted in participating in ethical requirements in areas of confidentiality, data considered and protection of research studies and institutional research approval in order to protect research integrity.

VII. Conclusion And Future Directions

Conclusion

This paper suggests a secondary, quantitative method to assess the hypothesis of longitudinal CPM trends providing good early warning on schedule risk of milestones. Through practical testing of Float Erosion rate, float runway, Runway Ratio and its performance

indicators to the results of past milestones the study aims at enhancing predictive project control, as well as establishing the opportunity to provide early evidence-based intervention in construction projects.

Future Research Directions

Further studies are recommended to test the framework on bigger and more varied datasets on constructions, type of projects and various schedule complexities [30]. Research ought to investigate other thresholds of Runway Ratio, logic switching effects and predictor combinations. Subsequent studies can combine Monte Carlo simulation of schedule-risk in conjunction with the implementation of advanced predictive analysis to enhance the quality of the warning as well as mitigating the false-positive and false-negative projects.

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