International Journal of Sustainability and Innovation in Engineering (IJSIE)
https://www.doi.org/10.56830/IJSIE2026
Vol. 4 2026

Integrated Cost-Schedule-Procurement Risk Index: A Framework and Validation Protocol for Hyper-Scale Data-Center Construction

https://www.doi.org/10.56830/IJSIE202619

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Received:23 July, 2026, Accepted:31h October, 2026, Published: 18th November, 2026

Abstract*:*

Hyperscale data-center projects combine high capital cost, compressed schedules, specialized long-lead equipment, and global supply chains. Conventional project controls review cost, schedule, procurement, and operational measures separately, so deterioration that starts upstream, for example in procurement, may appear in the Cost Performance Index (CPI) and Schedule Performance Index (SPI) only after it has become costly to recover. This paper proposes the Integrated Cost-Schedule-Procurement Risk Index (ICSP-RI), a composite early-warning index for hyperscale data-center construction, together with a protocol for developing and validating it. The framework starts from 42 candidate indicators in four categories (cost, schedule, procurement, and operational), which are screened, normalized to a common 0–1 risk scale, weighted, and aggregated into a project-level score. The paper specifies the normalization and aggregation formulas, the procedure for estimating weights, provisional risk classes, and a validation design that compares the index with CPI and SPI alone and with a baseline model that combines CPI, SPI, and the procurement variables. Because real project records could not be used, the protocol is demonstrated on synthetic data from a simulation of 40 projects over 24 monthly periods in three scenarios. The demonstration shows that the pipeline runs end to end and behaves sensibly: the index is more accurate than earned-value indicators alone when procurement or operational signals carry information, and shows no gain when they do not. However, the composite performs about as well as using all retained indicators without aggregation, and in the scenario where procurement and execution stress both drive outcomes, it did not meet the pre-specified criterion of improving on a baseline that combines earned-value and procurement indicators. No results from real projects are reported, and the simulation results follow from its stated assumptions.

Index Terms: Hyperscale Data Centers; Construction Risk Management; Early-Warning Systems; Earned Value Management; Integrated Risk Index.

1. Introduction

The characteristics of a high investment demand, shorter timelines and schedules, complicated building systems, and, thirdly, reliance on global supply chains have made this delivery on Big Data Centers a more complex approach to delivering high capital-intensive projects. Wherever there is a data center, there is also a building project, but in hyperscale data centers, the delivery of electrical, mechanical, cooling, structural, information-technology, and commissioning systems must be coordinated into an integrated delivery under highly constrained schedules. Project performance is thus not just about managing

direct construction work, but about ensuring that there are alignment issues also in place between cost, schedule, procurement, engineering, subcontractor performance, and decision making of projects. These qualities are a tremendous risk of cost overruns and schedule delays, especially in relation to critical equipment and connected activities.

Although cost and schedule control are not the priorities anymore, the engineering, procurement and construction (EPC) project management is running the same path. Traditional project-control systems use a variety of metrics like Cost Performance Index (CPI), Schedule Performance Index (SPI), cost variance, schedule variance, and critical-path float to gauge project performance relative to their approved baselines. Although these measures provide important information about current performance, they are frequently interpreted independently. Deterioration in one project area then, cannot therefore be sufficiently related to new issues that arise in another. A long lead time for an electrical or mechanical component to provide for the project, for instance, can be tackled as a procurement issue and then later impact critical-path activities, commissioning dates, labor usage, change orders and project costs.

A distinction therefore matters between lagging and leading indicators in complex construction projects. A reported cost overrun is a performance problem that has already occurred, whereas rising change-order volume, falling procurement readiness, shrinking critical-path float or recurring subcontractor problems may precede it. Construction research has increasingly examined leading indicators as a way of identifying developing problems before they become major (Haji-Kazemi et al., 2013; Zheng et al., 2019). To the best of the authors' knowledge from the literature reviewed in Section 2, cost, schedule, procurement and operational data have not been combined into a single quantitative early-warning index that is validated against CPI and SPI. Earned Value Management (EVM) is the established method for measuring cost and schedule performance through CPI and SPI (Fleming & Koppelman, 2010), but it does not directly measure procurement exposure or other upstream factors that may lead to later deterioration.

This is especially significant for the building of hyperscale data centers, for which specially designed power systems, cooling, switchgear, generator, transformer, and other large systems might have long lead times. If one item of work critical item is delayed this can cascade or cascade through the installation, testing and commissioning and handover processes. Procurement disruption may also generate additional expenditure through expediting, redesign, resequencing, temporary works, labour inefficiencies, and contractual changes. This can therefore lead to the ability to hide significant interdependencies between project risks through monitoring that separates the cost and schedule performance from procurement performance monitoring.

A set of management problems this study tackles is thus cost, schedule, procurement and operational performance monitoring issues. Ongoing reporting requirements for cost and schedule performance might be met in a project as procurement progression slows, critical-path float is reducing, cost of RFI activities increases, change-orders increase, or subcontractors underperform. These conditions may not be apparent until the costs or schedules show up, when it may be more difficult to act on them. Thus, there is a need for a quantitative framework that transforms several project-control measures into a single project-level risk measure, which is both practical and realistic.

To address this gap, the paper develops the Integrated Cost-Schedule-Procurement Risk Index (ICSP-RI) as a proposed early-warning framework for hyperscale data-center construction projects. The framework starts from 42 candidate indicators of cost control, schedule performance, procurement readiness and operational performance. These are screened, normalized and weighted to define an integrated risk score, which is intended to be tested against actual project outcomes and against conventional measures such as CPI and SPI. The paper has three objectives: to specify how the ICSP-RI is constructed (indicator categories, normalization, weighting and aggregation); to specify a validation design that can show whether the index adds predictive value beyond CPI and SPI; and to set out the provisional risk classes and the way they will be calibrated. The paper does not report results from real projects; it demonstrates the protocol on synthetic data from a simulation.

The intended application is completed hyperscale data-center construction projects, with cost overruns and schedule delays as the outcomes of interest. The ICSP-RI does not attempt to replace traditional methods such as EVM or Primavera scheduling. Rather, it is designed as an add-on decision-support tool that uses data already produced in the project-control process. The remainder of the paper reviews the literature, presents the research design, describes the index framework, presents a simulation-based demonstration and its limits, and closes with conclusions, limitations and recommendations.

2. Literature Review

2.1. Cost and Schedule Performance Measurement

Cost and schedule are the basic dimensions of construction project performance measurement. Earned Value Management (EVM) integrates planned value, earned value and actual cost into performance indicators (Fleming & Koppelman, 2010). The Cost Performance Index (CPI) measures cost efficiency and the Schedule Performance Index (SPI) measures schedule efficiency, and project teams use both to detect deviations from the approved baseline and to trigger corrective action. Both indices have known limits as forecasting tools. SPI is based on value rather than time, so it tends toward 1.0 as a project nears completion even when the project finishes late, which motivated the earned schedule method (Lipke, 2003). Simulation work shows that the accuracy of EVM-based duration forecasts depends on the level of project uncertainty, the network structure and the stage at which the forecast is made (Vanhoucke & Vandevoorde, 2007), and risk-adjusted estimates at completion have been proposed to bring risk information into EVM (Babar et al., 2017). CPI and SPI nevertheless report performance that has already been achieved and do not directly show emerging procurement or operational exposure.

2.2. Construction Risk and Early-Warning Systems

Construction projects carry technical, financial, contractual, organizational and schedule risks. Early-warning approaches aim to identify deteriorating project conditions before they lead to significant failure. Haji-Kazemi et al. (2013) review the approaches available for detecting early warning signs in projects, including EVM, performance measurement and risk management, and discuss the strengths and weaknesses of each. Later work shows that detection alone is not sufficient, because organizational factors can filter or delay responses to warning signs that have been identified (Haji-Kazemi et al., 2015). Leading indicators have been proposed to improve project performance measurement (Zheng et al., 2019), and Soliman et al. (2024) combine risk management with an earned value framework

to detect early warning signs in a case study. To the authors' knowledge, the works above do not report a single validated quantitative score that combines procurement and operational signals with CPI and SPI.

2.3. Procurement and Long-Lead Equipment Risks

Procurement is an important source of uncertainty in projects that depend on specialized equipment with long manufacturing and delivery periods. In engineering, procurement and construction (EPC) projects, much of the major equipment is engineered to order, so its lead times are generally longer than for off-the-shelf products and a delay in procurement can cascade through the construction schedule (Sandilya & Varghese, 2016). Delays to major electrical, mechanical or cooling systems therefore affect the critical path, installation sequences and commissioning. Álvarez-Pozo et al. (2024) analyze the causes of delays and cost overruns in turnkey industrial projects and the measures proposed to mitigate them. The studies reviewed here identify procurement as a driver of delay. To the authors' knowledge, they do not define a procurement indicator that is combined with CPI and SPI in a single early-warning score.

2.4. Composite Indicators and Research Gap

Composite indicators combine several individual indicators into a single score and are widely used to summarize multidimensional conditions. The OECD/JRC handbook on composite indicators (Nardo et al., 2008) sets out the main construction steps: a theoretical framework, data selection, normalization, weighting, aggregation, and robustness and sensitivity analysis. The ICSP-RI follows these steps. Data-driven frameworks that combine schedule and cost information to assess project risk have also been proposed (Arju & Rahman, 2023). The ICSP-RI extends this idea by adding procurement and operational indicators and by specifying a validation design that tests the composite against CPI and SPI.

The research gap addressed here is therefore the lack of a specified and testable early-warning index that integrates cost, schedule, procurement and operational signals. Whether such an index gives earlier or more accurate warning of cost and schedule problems than CPI and SPI monitoring is an empirical question. This paper does not answer it. It provides the specification and validation design needed to test it.

3. Methods and Techniques

3.1. Research Design and Data Requirements

The proposed study is quantitative and applied. It is a retrospective, longitudinal analysis of completed hyperscale data-center construction projects in which monthly or weekly reporting periods are nested within projects. The aim is to build and test the ICSP-RI as a tool for early warning of cost overruns and schedule delays. The planned data sources are Primavera P6 schedule data, cost reports, EVM metrics, procurement logs, long-lead equipment trackers, Requests for Information (RFIs), change orders, subcontractor performance records, and critical-path float data. These sources cover cost performance, schedule conditions, procurement exposure, and operational exposure.

When the protocol is applied, the study will report the number of projects and reporting periods, their locations, their size (for example, contract value or installed capacity), their execution dates, the origin of each data source, and any exclusion criteria. These descriptors

are not given here because real project data are not used in this paper; Section 5 uses synthetic data.

The methodology has five phases: (1) data collection and preparation; (2) indicator screening; (3) normalization and weighting; (4) index construction; and (5) validation against observed project outcomes. The workflow follows the construction steps recommended for composite indicators (Nardo et al., 2008) and is shown in Figure 1. Its purpose is to ensure that the index rests on objectively measured project attributes and not only on subjective assessment.

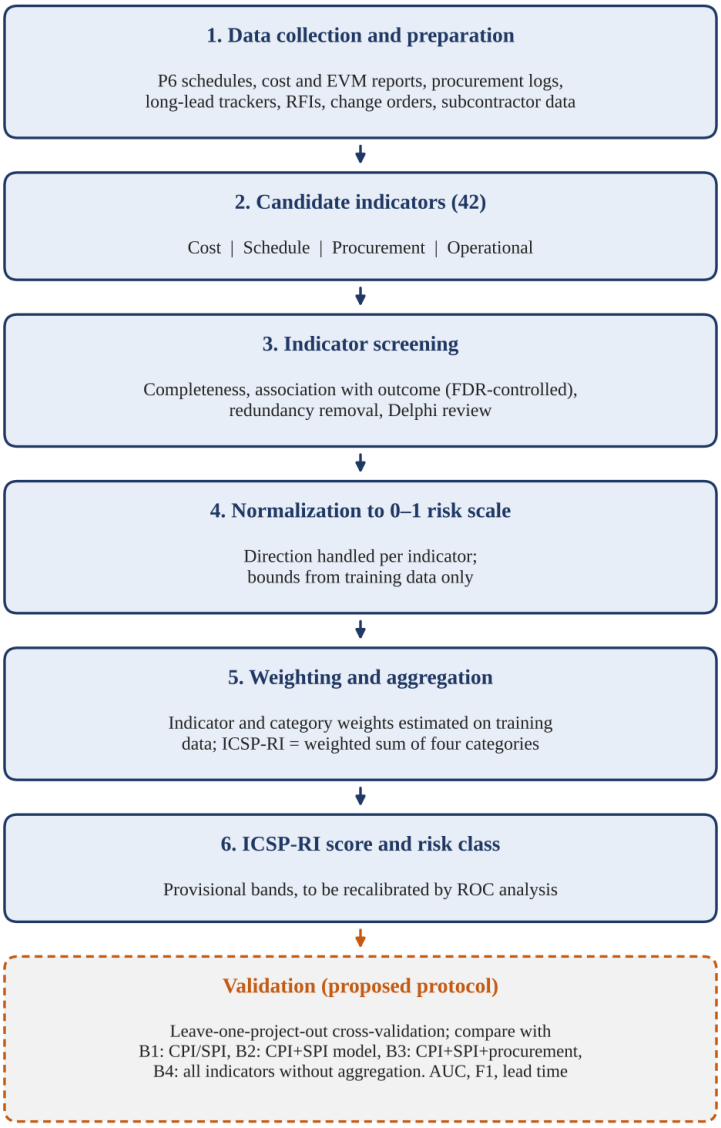


Figure 1. Proposed ICSP-RI development and validation workflow

Table 1 illustrates the research methodology used to develop and validate the ICSP-RI. It condenses the quantitative research design, primary project data sources, categories of indicators, and selected steps for data collection, data screening, data weighting, and indicator creation and indicator validation into a single document.

Table 1. Research Methodology

Component	Summary
Design	Quantitative applied research
Data Sources	P6 schedules, cost reports, EVM, procurement logs, RFIs and change orders
Indicators	Cost, schedule, procurement and operational indicators
Process	Data collection → screening → weighting → ICSP-RI development → validation

3.2. Indicator Selection and Construction

The study begins with 42 candidate indicators arranged in four categories: cost, schedule, procurement and operational performance. Cost indicators include CPI and cost variance. Schedule indicators include SPI, schedule variance and critical-path float. Procurement indicators include long-lead equipment exposure, procurement readiness and delivery status. Operational indicators include RFI closure, change-order frequency and subcontractor performance. Table 2 gives the proposed definition and risk direction of these indicators. The full list of the 42 candidates, with definitions and units, will be provided as a supplementary table. Indicator choice draws on the literature on project key performance indicators (Petraitis, 2025) and on leading indicators (Zheng et al., 2019).

Table 2. Examples from the Candidate Indicator Set, with Proposed Definitions and Risk Direction

Category	Indicator	Proposed definition	Higher risk when
Cost	CPI	EV / AC	Lower
Cost	Cost variance (CV)	EV − AC	More negative
Schedule	SPI	EV / PV	Lower
Schedule	Schedule variance (SV)	EV − PV	More negative
Schedule	Critical-path float	Total float on the critical or near-critical path (days)	Lower
Procurement	Long-lead equipment exposure	Share of long-lead order value with forecast delivery later than the required on-site date	Higher
Procurement	Procurement readiness	Share of packages due for award or release that are on plan	Lower
Procurement	Delivery status	Share of expected deliveries received on or before the planned date	Lower
Operational	RFI closure	Share of open RFIs past their response due date	Higher
Operational	Change-order frequency	Number of change orders issued per reporting period	Higher
Operational	Subcontractor performance	Earned value / planned value of subcontracted work	Lower

EV = earned value; AC = actual cost; PV = planned value. Definitions are proposed and will be confirmed with the Delphi panel before data analysis.

Indicators are screened in four steps, with all cut-offs fixed before the outcome data are analyzed and reported with the results. First, an indicator is retained only if it is observed in at least 80% of reporting periods. Second, its association with the later outcome (Section 3.4) is tested with Spearman rank correlation, controlling the false discovery rate at 5% across the 42 tests, and a minimum absolute correlation of 0.20 is required; Pearson correlation is reported alongside. Third, redundancy is removed: where two indicators have an absolute rank correlation above 0.80, or a variance inflation factor above 5, the one judged more actionable by the expert panel is kept. Fourth, a multivariable regression of the outcome on the remaining indicators confirms which of them add explanatory information.

A Delphi panel then reviews the retained set for practical meaning and for the direction of each indicator (Okoli & Pawlowski, 2004). The panel will have 10 to 15 experts with at least ten years of experience in project controls, procurement or construction management on hyperscale or comparable mission-critical projects. Up to three rounds are run. Consensus on an item is defined as an interquartile range of 1 or less on a five-point scale, and Kendall's W is reported for each round. Panel size, expertise, number of rounds, and consensus statistics will be reported with the results.

3.3. Normalization, Weighting and Aggregation

The retained indicators use different units and scales, so each is normalized to a 0–1 risk score before aggregation. Let x(i,t) be the raw value of indicator i in reporting period t. If a higher raw value means higher risk (for example, change-order frequency), the normalized score is:

$$r(i,t) = [x(i,t) - L(i)] / [U(i) - L(i)]$$

If a lower raw value means higher risk (for example, CPI, SPI, or critical-path float), the score is:

$$r(i,t) = [U(i) - x(i,t)] / [U(i) - L(i)]$$

In both cases, r(i,t) is truncated to the interval [0, 1]. The bounds L(i) and U(i) are the 5th and 95th percentiles of indicator i in the training data only, so that no information from test projects or from future periods enters the index (Section 3.4). The direction of each indicator is set in Table 2 and confirmed by the expert panel. Min–max normalization with these bounds is the primary method, and z-score normalization is used as a sensitivity check. The category score is the weighted sum of its normalized indicators, and the index is the weighted sum of the four category scores:

$$S(c,t) = \Sigma\, w(i) \cdot r(i,t), \text{ over the indicators i in category c, with } \Sigma\, w(i) = 1 \text{ within each category}$$

$$ICSP\text{-}RI(t) = W(cost)\cdot S(cost,t) + W(schedule)\cdot S(schedule,t) + W(procurement)\cdot S(procurement,t) + W(operational)\cdot S(operational,t), \text{ with the four W values summing to 1}$$

The indicator weights w(i) and the category weights W(c) are estimated from the training data using the standardized coefficients of the multivariable model, constrained to be

non-negative and rescaled to sum to one. The Delphi panel reviews these weights for plausibility and provides an independent second weight set that is compared with the first in the sensitivity analysis. Linear aggregation is compensatory, so a low-risk indicator can offset a high-risk one; a geometric aggregation (Nardo et al., 2008) is therefore also tested. The weights, normalization bounds and estimation sample will be reported with the results.

3.4. Validation Design

Outcome. The outcome is defined for each reporting period. A period is labelled as followed by an adverse event if, within the next H reporting periods, the cumulative cost overrun reaches θcost percent of the approved budget or the schedule slip reaches θschedule days beyond the approved baseline completion date. H, θcost and θschedule will be fixed before analysis and justified from contract practice, such as contingency levels and delay-damages exposure. Results will also be shown for other thresholds and horizons so that readers can judge their sensitivity.

Unit of analysis. The unit of analysis is the project-reporting period. Because periods from one project are correlated, confidence intervals are computed by bootstrap resampling of whole projects and not of individual periods.

Prediction horizon and leakage. Every indicator in period t uses only information available at the reporting cut-off date of period t. The outcome is observed in periods t+1 to t+H. Screening, normalization bounds and weights are estimated on training projects only, within each validation fold, so no information from test projects or from later periods enters the index.

Validation with a small number of projects. Random k-fold validation over periods would place periods from the same project in both the training and test sets and overstate accuracy. The protocol therefore uses leave-one-project-out cross-validation, or grouped k-fold validation where the number of projects allows (Hastie et al., 2009). A separate hold-out set of projects is used only if enough projects and events remain for stable estimation. The numbers of projects and adverse events in each fold will be reported. If they are too small for stable weight estimation, the results will be presented as exploratory.

Baselines. Because the ICSP-RI contains CPI and SPI as inputs, outperforming CPI and SPI alone would not show that integration adds value. The index is therefore compared with three baselines: B1, CPI or SPI used alone; B2, the four earned-value indicators (CPI, SPI, CV and SV) combined in a logistic regression; and B3, the same four indicators plus the procurement variables in a logistic regression. A fourth reference model, B4, uses all retained indicators in a logistic regression without aggregation into a composite. The ICSP-RI is judged on whether it improves on B3, and B4 shows what, if anything, is lost by reducing the indicators to one score.

Metrics and thresholds. Performance is reported as the area under the ROC curve (Fawcett, 2006), with precision, recall and F1 at the selected threshold, the correlation between the index and the outcome, and early-warning lead time, defined as the number of periods between the first time the index enters the high-risk class and the first adverse event. The risk-class boundaries in Section 4.2 are provisional. They will be recalibrated using ROC analysis and, where a missed warning costs more than a false alarm, cost-sensitive cut-offs (Fawcett, 2006). The alarm threshold used for detection and lead time is set so that 20% of event-free periods trigger an alarm, which puts all methods at the same false-alarm rate. The

index is judged to add value only if (i) its AUC exceeds that of B3 with an interval for the difference that excludes zero, and (ii) it detects a larger share of events at the same false-alarm rate with a longer lead time. If these conditions are not met, the conclusion is that integration does not improve on the simpler baseline. Sensitivity analysis will cover the weights (a ±20% perturbation and the Delphi weight set), the normalization method, the aggregation form and the outcome thresholds.

4. ICSP-RI Framework Development and Application

4.1. Indicator Selection and Weighting

Indicators representing the main factors that affect project performance are selected and fed into the ICSP-RI. The framework groups the indicators into four categories: cost, schedule, procurement and operational. The selection procedure starts from the 42 candidate indicators and uses statistical screening, regression and a Delphi review, as described in Section 3.2.

The weights reflect the contribution of each indicator and each category to the prediction of project outcomes. They are not fixed in advance: indicator weights and the four category weights (cost, schedule, procurement and operational) are estimated from the development data as described in Section 3.3. No weights are reported in this paper because the estimation has not been carried out. The operational indicators (RFIs, change orders and subcontractor performance) form a full fourth component of the index and carry their own category weight. Any weights reported in later work will be accompanied by the estimation sample and the results of the sensitivity analysis.

The resulting index gives a unified picture of project exposure. The project with more indicators that have deteriorated, say, declining cost performance, schedule performance, increasing long-lead equipment exposure, and reduced operational performance can, therefore, score a higher ICSP-RI as compared to the project where only one indicator is lacking.

4.2. Risk Classification

The ICSP-RI provides four provisional risk classes: low, moderate, high and critical. The provisional bands are equal-width quartiles of the 0–1 scale: low for scores from 0 up to but not including 0.25, moderate from 0.25 up to but not including 0.50, high from 0.50 up to but not including 0.75, and critical from 0.75 to 1.00. These bands have not been calibrated against project outcomes. They will be replaced by data-based boundaries from the ROC analysis described in Section 3.4. A low score means that cost, schedule, procurement and operational conditions are relatively under control. A moderate score shows some signs of deterioration that warrant closer monitoring. A high score indicates a combination of adverse conditions that may justify corrective intervention, and the critical class is for substantial exposure that needs urgent attention.

For early-warning applications, the classification is of particular relevance since the index aims to make it possible to identify deteriorating performance before it comes to a full realization in final cost and schedule results. The framework is not just a methodology based on achieved milestones and historical deviation, but a mix of ‘leading' indicators and ‘performance' indicators which give an earlier warning on potential issues with projects.

The provisional classification is presented in Table 3, with index scores from 0.00 to 1.00 mapped to low, moderate, high, and critical risk, together with the interpretation and the recommended management response for each class.

Table 3. ICSP-RI Provisional Risk Classification Levels

ICSP-RI Score	Risk Level	Interpretation	Recommended Management Response
0.00 to <0.25	**Low**	Cost, schedule, procurement, and operational conditions remain relatively controlled.	Continue routine monitoring and project controls.
0.25 to <0.50	**Moderate**	Emerging deterioration is evident and may develop into more significant project risk.	Increase monitoring and investigate contributing indicators.
0.50 to <0.75	**High**	Multiple adverse conditions indicate increased exposure to cost or schedule deterioration.	Initiate corrective actions and strengthen management oversight.
0.75 to 1.00	**Critical**	Substantial project exposure exists across one or more performance dimensions.	Requires immediate management attention and corrective intervention.

4.3. Operational Application and Dashboard Integration

The ICSP-RI is not intended as a reporting system in its own right but as an add-on to the monitoring that projects already carry out. Project data can be compiled from project-management records, schedules, cost-control systems, procurement trackers, RFI records, and change-order registers. Primavera P6, Python, R, Power BI, Excel and SPSS can support data processing, analysis, visualization and validation, and dashboard approaches to construction project control have been described in the literature (Abdulaziz & Ahmed, 2026).

The operational sequence of the framework is Data Collection, Indicator Screening, Normalization, Weighting, ICSP-RI Calculation, Risk Classification and Management Response. The resulting dashboard presents the overall risk level alongside the contribution of individual categories, enabling project teams to identify whether risk is primarily associated with cost performance, schedule deterioration, procurement exposure, or operational conditions.

The framework therefore connects the quantitative measure to project decision-making. If validated, the ICSP-RI can be monitored on an ongoing basis, and changes within categories can direct focused investigation and corrective action. This extends the performance reporting traditionally provided by CPI and SPI to additional dimensions of project risk, in line with approaches that combine risk management and earned value to detect early warning signs (Soliman et al., 2024).

5. Simulation-Based Demonstration

Real project records cannot be used in this paper, so the protocol of Section 3 is demonstrated on synthetic data. The purpose is to show that the pipeline runs end to end, to show how its outputs are read, and to test whether it behaves sensibly when the underlying signals are present and when they are absent. The simulation is not empirical evidence about

real projects, and none of its numbers should be read as estimates of how the ICSP-RI would perform in practice.

5.1. Simulation Design

Each simulated dataset contains 40 projects with 24 monthly reporting periods. Two latent stress processes, procurement stress and execution stress, evolve as autoregressive series. Cumulative slippage grows with execution stress (one-month lag) and, in Scenario A, also with procurement stress (two-month lag). The eleven indicators of Table 2 are generated from the latent processes and from slippage, with random noise. CPI, SPI, CV and SV respond to slippage that has already accumulated, so they lag. Critical-path float, the procurement indicators and the operational indicators respond to the latent stress processes, so they lead. An adverse event is the first time slippage reaches a fixed threshold, and a period is labelled positive if the event occurs within the next H = 3 periods; periods after the event are excluded. Simulation has been used in this way before to evaluate earned-value forecasting metrics (Vanhoucke & Vandevoorde, 2007).

Three scenarios are run. In Scenario A, both procurement stress and execution stress drive slippage. In Scenario B, only execution stress does, so procurement is irrelevant. In Scenario C, the leading indicators are generated from independent processes and carry no information about slippage. Each scenario is repeated for 30 simulated datasets. The full protocol is applied to every dataset, including leave-one-project-out cross-validation, with screening, normalization bounds and weights estimated on training projects only. The baselines are those defined in Section 3.4.

5.2. Results

Table 4 gives the mean AUC over the 30 datasets of each scenario, with the 2.5th and 97.5th percentiles across datasets. In Scenario A, the ICSP-RI (0.91) was more accurate than CPI or SPI alone (0.75 and 0.72) and than the earned-value model B2 (0.84). Its advantage over B3 was 0.02, with a range across datasets of -0.01 to 0.07, so the interval for the difference includes zero, and the pre-specified criterion of Section 3.4 was not met. In Scenario B, the ICSP-RI exceeded B3 by 0.07 (range 0.04 to 0.09). This gain comes from the operational indicators, which B3 does not contain, and shows the cost of omitting a driver category, not an advantage of aggregation. In Scenario C, where the leading indicators are uninformative, the ICSP-RI (0.87) was no better than B3 (0.86), as it should be.

Table 4. Mean AUC by Scenario and Model (2.5th–97.5th Percentile Across 30 Simulated Datasets)

Model	Scenario A	Scenario B	Scenario C
B1: CPI alone	0.75 (0.71–0.79)	0.76 (0.71–0.80)	0.76 (0.71–0.81)
B1: SPI alone	0.72 (0.66–0.77)	0.73 (0.68–0.77)	0.73 (0.68–0.77)
B2: EVM indicators	0.84 (0.80–0.89)	0.87 (0.83–0.91)	0.86 (0.83–0.91)
B3: EVM + procurement	0.88 (0.85–0.91)	0.87 (0.83–0.91)	0.86 (0.83–0.90)
B4: all, no composite	0.91 (0.89–0.94)	0.93 (0.89–0.95)	0.85 (0.82–0.90)
ICSP-RI	0.91 (0.86–0.93)	0.93 (0.91–0.95)	0.87 (0.83–0.91)

Table 5 gives the share of adverse events that were detected before or at the start of the pre-event window, and the median lead time in periods, when the alarm threshold produces a 20% false-alarm rate. The ICSP-RI detected 86% of events in Scenario A against 77% for B3 and 63% for B2, and 98% in Scenario B against 80% for B3. Its median lead time was not longer than that of B3 in either scenario, so the second part of the pre-specified criterion was not met. In Scenario C, the detection shares were similar for all models.

Table 5. Share of Events Detected and Median Lead Time in Periods at a 20% False-Alarm Rate

Model	Scenario A	Scenario B	Scenario C
B2: EVM indicators	63% (1.8)	81% (3.2)	79% (3)
B3: EVM + procurement	77% (1.5)	80% (3)	79% (3.5)
B4: all, no composite	88% (1)	97% (3)	78% (3.2)
ICSP-RI	86% (1)	98% (3)	80% (3)

Figure 2 shows the ROC curves for one dataset of Scenario A and the AUC values of the four main models in all scenarios. Figure 3 shows the ICSP-RI and the risk-scaled CPI and SPI for one simulated project, the first one in the dataset with an event in the middle of the horizon. The ICSP-RI trends upward before the event and is less erratic than the CPI and SPI series. This single project is illustrative and was not selected to measure performance.

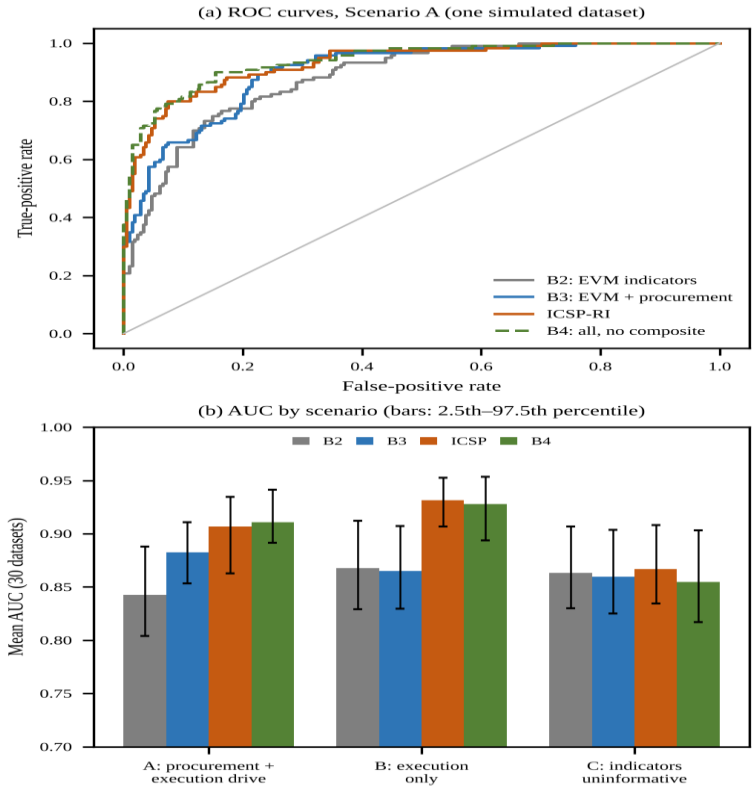


Figure 2. ROC Curves (Scenario A) and AUC by Scenario

Table 6 shows the category weights that the procedure of Section 3.3 estimated, averaged over the cross-validation folds and datasets. The weights follow the structure of each scenario. Procurement receives weight only in Scenario A, and in Scenario C the procurement and operational categories receive no weight because screening removed their indicators. This is the intended behaviour, but it is a property of the simulation and not an estimate for real projects.

Table 6. Mean Estimated Category Weights by Scenario

Category	Scenario A	Scenario B	Scenario C
Cost	0.37	0.36	0.59
Schedule	0.31	0.28	0.41
Procurement	0.14	0.00	0.00
Operational	0.19	0.36	0.00

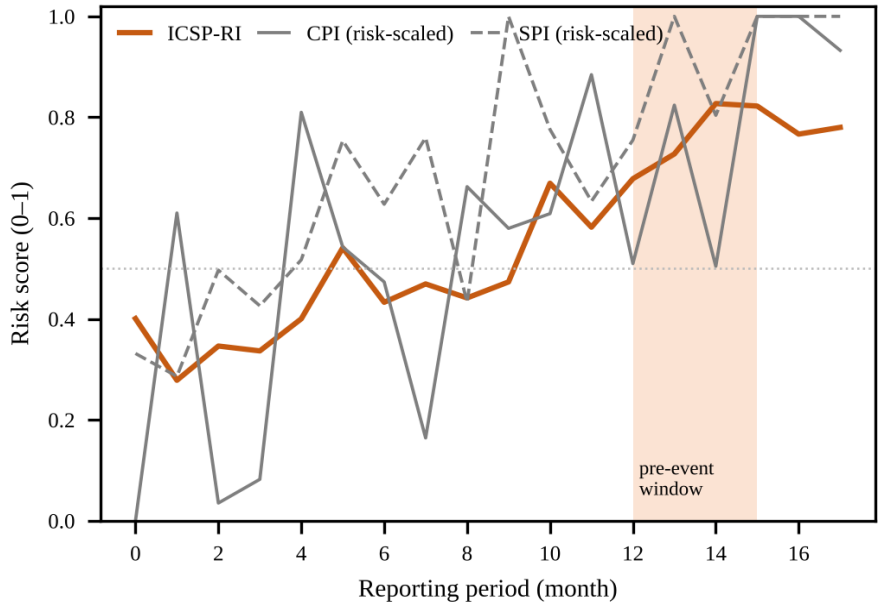


Figure 3. ICSP-RI and Risk-Scaled CPI and SPI for One Simulated Project

5.3. Interpretation and Limitations

Under the pre-specified rule of Section 3.4, the simulation did not show that the ICSP-RI adds value over B3. In Scenario A, the interval for the AUC difference included zero, and the lead time was not longer. In Scenario B, the AUC gain over B3 came from operational indicators that B3 omits. The ICSP-RI also performed about as well as B4, which uses all retained indicators without aggregation (Table 4). In these simulations, the value of the composite is therefore a single, interpretable score with stable weights, and not higher accuracy than a model on the same indicators.

The demonstration has clear limits. Every result follows from the assumptions of the data-generating process: the lags, noise levels and effect sizes were chosen by the authors and are not estimated from real projects. Real data have missing values, structural breaks, correlated indicators and reporting practices that the simulation does not capture. The 20% false-alarm rate was applied to pooled test scores, and the provisional risk bands of Section

4.2 were not evaluated. The intervals in Table 4 are taken across simulated datasets and not from a project-level bootstrap. The simulation therefore shows how the method behaves under known conditions, and it does not show that the method works on real projects.

5.4. Practical Implications

If the validation on real projects supports it, the framework has practical relevance for project managers, commercial teams, planners, procurement managers and construction-control personnel working on hyperscale data-center projects. Information produced by cost control, scheduling, procurement, engineering and site-management systems in periodic project reviews can be used to compute the ICSP-RI. A higher score would lead management to examine critical procurement packages, schedule float, change orders, RFIs, subcontractor performance and other contributing factors more closely.

The framework could therefore support a shift from end-of-project reporting toward more active risk monitoring. Its main use is not to replace CPI, SPI or existing scheduling systems but to combine information from them with procurement and operational signals into a common quantitative view of emerging project risk. Integrated supply-chain platforms may help to provide the required data (Ekhlasi, 2024).

6. Conclusion and Recommendations

6.1. Conclusions

Hyperscale data-center projects carry interdependent risks. A procurement delay, for example, can add cost through expediting and resequencing, disrupt engineering and subcontractor work, and expose the critical path. Monitoring cost, schedule, procurement and operational measures separately may therefore not fully reflect project risk. This paper proposed the Integrated Cost-Schedule-Procurement Risk Index (ICSP-RI) as a way of combining selected indicators from these dimensions into a single standardized and weighted score, while keeping existing cost and schedule monitoring in place.

The contribution of the paper is the specification of the index and of how it is tested: four indicator categories, the normalization and aggregation formulas, a procedure for screening indicators and estimating weights, provisional risk classes, a validation design with project-level cross-validation and baselines that include the earned-value and procurement indicators, and a simulation-based demonstration of the whole pipeline.

Real project data were not used. A simulation with synthetic data showed that the pipeline runs end to end, that the index is more accurate than earned-value indicators alone when procurement or operational signals carry information, and that it shows no gain when they do not. It did not outperform the unaggregated model B4 and, in the scenario where procurement and execution stress both matter, it did not meet the criterion of improving on B3. These results follow from the assumptions of the simulation and are not evidence about real projects. The main limitations are that a small number of projects may limit stable weight estimation, that the index contains CPI and SPI as inputs, that the risk-class boundaries are provisional, and that the index can show association but not causation.

The framework is intended for decision support and not as a substitute for professional judgment. A high score does not guarantee a particular outcome, and a single reporting period reflects short-term conditions and not long-term deterioration. Use requires regular data

validation, an understanding of the project setting and sound cost, schedule, procurement and contract management systems.

6.2. Recommendations

The ICSP-RI should be seen as a guide for further development of standard hyper-scale data center data structures. The following could be standardized in order to compare a project's procurement readiness, critical-path float, change-order frequencies, the performance of RFIs, cost-variance measures, and schedule-variance measures for various projects and reporting periods for a single project. Manual data processing requirements may also be reduced by automated data provided by enterprise project-management, procurement, cost-control, and scheduling systems.

This index too needs an update when larger project data sets can be generated. The evolution of hyperscale datacenter construction also is unfolding with technology advancements to building equipment, revision of the supply chain, construction techniques, and commissioning requirements. Then, if these project conditions are changing, project indicators should also be adjusted accordingly. This would require indicator weights to periodically be recalibrated and risk thresholds to be periodically updated. The immediate next step is to apply the protocol to a sample of completed real hyperscale projects and to report the results, including the indicator list, weights, thresholds, and validation metrics. Further research can test the index on a larger dataset from other geographies. Using monthly or weekly reporting periods would allow closer analysis of the delay between a change in risk score and project outcomes. Machine learning and probabilistic methods could be explored as extensions of the weighted index. Contribution - Proposes and specifies an integrated early-warning index for hyperscale data-center construction, together with a validation design and a simulation-based demonstration of whether integrating cost, schedule, procurement, and operational signals adds predictive value beyond earned-value indicators. Validation on real project data remains to be done.

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