

Integrating Critical Path Scheduling and Resource Optimization in Building Construction Projects: A Risk-Based Project Delivery Framework

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Abstract

Building construction projects routinely miss contractual completion dates even when they are planned with the critical path method, because deterministic schedules assume unlimited resources and ignore the uncertainty attached to recurring delay causes. This study develops a risk-based project delivery framework that integrates critical path scheduling, resource-constrained optimisation, construction risk and delivery performance measurement. A structured narrative review of scheduling, resource leveling, schedule risk, delay causation and earned value literature published up to 2021 identified four integration gaps located at the interfaces between these streams. The resulting four-layer framework links schedule logic, parallel resource and risk layers, an integration layer and a performance control layer through six testable propositions and fifteen formal equations, including a new risk-adjusted criticality index computed on the resource-constrained schedule. An illustrative, synthetic thirteen-activity building scenario, computed with a serial schedule generation scheme and 10,000 Monte Carlo replications, shows that leveling to a ten-worker crew extends the deterministic duration from 67 to 78 days, that the 80th percentile resource-constrained completion is 97 days, and that activities ranked highest for risk response differ from those identified by unconstrained analysis. The schedule performance index for identical progress ranged from 0.631 to 1.021 depending on the baseline adopted. The framework gives planners, project controls teams and owners a defensible sequence for building resource-feasible, risk-informed baselines.

Keywords: critical path method; resource-constrained project scheduling; resource leveling; schedule risk analysis; earned value management; construction delay; building construction

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1. Introduction

1.1 Background and Problem Context

The critical path method (CPM) of Kelley and Walker (1959), formalised by Kelley (1961), remains the backbone of construction planning, and the Program Evaluation and Review Technique (PERT) of Malcolm et al. (1959) supplied the first probabilistic treatment of durations. CPM is often contractually required (Galloway, 2006), yet overruns documented in Saudi Arabia (Assaf & Al-Hejji, 2006), Malaysia (Sambasivan & Soon, 2007), Jordan (Odeh & Battaineh, 2002), Hong Kong (Chan & Kumaraswamy, 1997), India (Doloi et al., 2012) and Nigeria (Aibinu & Jagboro, 2002) show that a correct network does not guarantee on-time delivery. Explanations include governance bottlenecks (Nwafor et al., 2019), forecasting optimism (Flyvbjerg et al., 2002; Flyvbjerg, 2014) and the unlimited-resource assumption of the classical forward and backward pass.

Three failure modes recur. Total float computed on an unconstrained network is consumed by resource conflicts, so apparently non-critical activities are resource-critical (Raz & Marshall, 1996; Kim & de la Garza, 2005). Deterministic schedules ignore merge-event bias (MacCrimmon & Ryavec, 1964). Earned value indicators such as the schedule performance index (SPI) and cost performance index (CPI) are computed against a baseline whose realism is rarely questioned (Fleming & Koppelman, 2010; Vandevoorde & Vanhoucke, 2006).

1.2 Research Gap and Novelty

The resource-constrained project scheduling problem (RCPSP) has mature classification schemes (Blazewicz et al., 1983; Brucker et al., 1999), heuristic benchmarks (Hartmann & Kolisch, 2000; Kolisch & Hartmann, 2006) and surveys of variants (Hartmann & Briskorn, 2010; Pellerin et al., 2020). Schedule risk analysis rests on Monte Carlo simulation (Van Slyke, 1963), criticality indices (Dodin & Elmaghraby, 1985; Williams, 1992) and correlated risk models (Ökmen & Öztaş, 2008). Delay research is largely survey-based and ranks causes without linking them to network position (Gündüz et al., 2013; Durdyev & Hosseini, 2020). Herroelen and Leus (2005) and Schatteman et al. (2008) called for integration, but no framework carries a delay cause through resource-constrained float and risk-adjusted criticality to earned value signals for building projects, with explicit equations and testable propositions.

The study makes three contributions: a four-layer risk-based project delivery framework linking schedule logic, resource constraints, construction risk and delivery performance; a risk-adjusted criticality index computed on the resource-constrained schedule, extending Elmaghraby (2000) and Bowers (1995) with a delay-cause exposure term (Al-Bahar & Crandall, 1990; Zou et al., 2007); and a thirteen-activity

illustration showing that the choice of baseline materially changes both forecast completion and the earned value signal.

1.3 Research Questions and Objectives

Three questions guide the study. RQ1: What does the pre-2022 literature establish about the interaction of critical path scheduling, resource optimisation, schedule risk and delay causation in building construction? RQ2: How can these constructs be integrated into a framework whose relationships can be expressed formally and tested? RQ3: How large is the difference between baseline, leveled and risk-adjusted schedules in a representative building project, and how does it propagate into earned value indicators? The review follows Tranfield et al. (2003), and scheduling vocabulary follows the Practice Standard for Scheduling (Project Management Institute, 2019) and the PMBOK Guide (Project Management Institute, 2017).

2. Review Protocol and Methodology

2.1 Review Design and Search Strategy

The study combines a structured literature review with conceptual framework development, a design suited to evidence that has not been integrated across disciplines (Tranfield et al., 2003). Because it maps constructs rather than pooling effect sizes, it does not follow the record-level reporting of a PRISMA systematic review (Moher et al., 2009). The operational research literature on scheduling, mathematical and often not construction-specific (Demeulemeester & Herroelen, 2002), and the empirical construction management literature were searched with comparable intensity in Scopus, Web of Science Core Collection and the ASCE Library to December 2021, the last covering construction scheduling studies such as Hegazy (1999) and Lu and Li (2003). Searches combined scheduling, resource, risk and construction-context concept blocks (Table 1). Seminal works such as Kelley and Walker (1959), Malcolm et al. (1959) and Wiest (1964), and the AACE practices on forensic schedule analysis (AACE International, 2011a) and integrated cost and schedule risk analysis (AACE International, 2011b), were added by backward citation tracking.

Table 1. Structured review protocol: sources, search strings, eligibility criteria and screening stages

Protocol element	Specification
Databases	Scopus; Web of Science Core Collection; ASCE Library (Journal of Construction Engineering and Management, Journal of Management in Engineering)
Time window	Inception to December 2021; seminal pre-indexing works (1959-1975) and professional standards added by citation tracking
Block A: scheduling	"critical path" OR CPM OR "total float" OR "free float" OR PERT OR "project schedul*"

Protocol element	Specification
Block B: resources	"resource-constrained" OR RCPSP OR "resource level*" OR "resource allocation" OR "resource-loaded"
Block C: risk and performance	"schedule risk" OR "Monte Carlo" OR "criticality index" OR delay* OR "earned value" OR SPI OR CPI
Block D: context	construction OR building OR contractor* (applied to the ASCE Library implicitly)
Search logic	A AND (B OR C) AND D for Scopus and Web of Science; A AND (B OR C) for the ASCE Library
Inclusion criteria	Peer-reviewed journal article, book or recognised professional standard; English language; addresses at least one target construct with an explicit model, algorithm or empirical method; relevance to building or general construction scheduling
Exclusion criteria	Manufacturing, software or computing scheduling without transferable construction relevance; cost estimating without schedule dimension; conference abstracts, editorials, theses and preprints
De-duplication	Records retrieved from more than one database merged before screening
Screening stage 1	Title and abstract screening against the inclusion and exclusion criteria
Screening stage 2	Full-text eligibility: at least one target construct and an explicit model, algorithm or empirical method
Citation chaining	Backward and forward citation tracking from eligible studies to recover seminal pre-indexing works and professional standards
Analysed corpus	The studies cited and coded in Sections 3.1 to 3.7, summarised in Tables 2 and 3

2.2 Screening, Synthesis and Quality Appraisal

Titles and abstracts were screened against the criteria in Table 1, and full texts were retained if they addressed network logic and float, resource constraints, schedule risk or delivery performance with an explicit method. Snowballing recovered studies missed through shifts in terminology, such as from "resource allocation" to "resource-constrained scheduling" (Herroelen et al., 1998). Studies were coded for scheduling representation, treatment of resources and uncertainty, delivery measure and setting; recurring constructs became framework layers and documented relationships became propositions, following Tranfield et al. (2003) and the uncertainty management logic of Ward and Chapman (2003). Existing formal models, such as the forward and backward pass of Kelley (1961), were adopted directly. Appraisal weighted confidence rather than excluding studies, since foundational theory such as Wiest (1964) scores poorly on empirical adequacy. Survey studies were checked for sample size and use of a relative importance index or factor analysis (Gündüz et al., 2013; Doloi et al., 2012), and model studies for testing on PSPLIB (Kolisch & Sprecher, 1997) or project data.

3. Thematic Synthesis

3.1 Critical Path Logic and Float

CPM establishes the activity network, the forward and backward passes and the derived total and free float (Kelley, 1961). Because total float is shared along a path, its consumption by one party reduces what

remains for others, a central issue in delay claims (AACE International, 2011a). Precedence diagramming with lags preserves this logic (Project Management Institute, 2019). Galloway (2006) found that practitioners value CPM chiefly for communication and claims and apply resource loading less consistently than logic, which makes the resource layer the weakest link in typical building schedules. The deterministic longest path also need not govern completion once durations vary, which motivated the criticality literature in Section 3.3.

3.2 Resource-Constrained Scheduling and Resource Leveling

Wiest (1964) showed that under resource limits the critical path becomes a critical sequence with technological or resource-driven links. The zero-one model of Pritsker et al. (1969) followed, Davis and Patterson (1975) compared priority rules with optimal solutions, and Blazewicz et al. (1983) proved the RCPSPP strongly NP-hard. Kolisch (1996) clarified serial and parallel schedule generation schemes, PSPLIB (Kolisch & Sprecher, 1997) standardised benchmarking, and Hartmann and Kolisch (2000) and Kolisch and Hartmann (2006) ranked heuristics. Construction leveling developed from Harris (1990) and Easa (1989) to genetic algorithms (Chan et al., 1996; Hegazy, 1999; Son & Skibniewski, 1999) and alternative objectives (El-Rayes & Jun, 2009). Lu and Li (2003) restored meaningful float on resource-loaded schedules, Kim and de la Garza (2005) evaluated float reporting in resource-constrained CPM, and Raz and Marshall (1996) showed that float computed without resources can mislead. Predictive forecasting of resource needs (Unamma et al., 2018) can narrow later leveling adjustments.

3.3 Schedule Risk Analysis and Criticality

PERT assigns beta-distributed durations from three estimates (Malcolm et al., 1959); MacCrimmon and Ryavec (1964) showed that it underestimates expected duration by ignoring near-critical paths, and Van Slyke (1963) proposed Monte Carlo simulation, which also yields the criticality index. Dodin and Elmaghraby (1985) approximated the index, Williams (1992) warned that criticality alone may misdirect attention, Elmaghraby (2000) separated criticality from sensitivity, Bowers (1995) extended it to resource-constrained networks, and Vanhoucke (2010) linked sensitivity and topology to control. For construction, Mulholland and Christian (1999) assessed schedule risk, Ökmen and Öztaş (2008) modelled correlated durations, and Hulett (2009) and AACE International (2011b) codified risk-driver simulation. Herroelen and Leus (2005) classified approaches to scheduling under uncertainty, all of which depend on structured hazard and risk identification (Obogo et al., 2019b). Criticality is rarely computed on a leveled schedule or weighted by the underlying delay cause.

3.4 Delay Causes in Building Construction

Delay research converges across settings. Owner change orders, slow payment, poor site management and labour shortages dominate in Saudi Arabia (Assaf & Al-Hejji, 2006); contractor planning and material shortages in Malaysia (Sambasivan & Soon, 2007); owner interference and financing in Jordan (Odeh & Battaineh, 2002); site management, ground conditions and slow decisions in Hong Kong (Chan & Kumaraswamy, 1997); and commitment and coordination in India (Doloi et al., 2012). Frimpong et al. (2003) and Aibinu and Jagboro (2002) documented payment and procurement effects in West Africa, Gündüz et al. (2013) quantified 83 factors in Turkey, Zidane and Andersen (2018) consolidated universal factors, and Durdyev and Hosseini (2020) synthesised 97 studies. Supply chain disruption in engineering, procurement and construction delivery also drives delay (Agbabiaka et al., 2019), especially for long-lead items. Table 2 maps recurrent causes to the construct through which each acts, a step these studies omit.

Table 2. Recurrent delay causes in building construction mapped to the framework construct through which they act

Delay cause	Supporting studies	Mechanism in schedule	Framework construct
Owner change orders and design changes	Assaf and Al-Hejji (2006); Odeh and Battaineh (2002)	Added scope and rework on specific activities	Layer 2b risk event (duration impact)
Late payment and financing difficulty	Aibinu and Jagboro (2002); Frimpong et al. (2003)	Reduced crew strength across activities	Layer 2a capacity reduction
Labour shortage and low productivity	Sambasivan and Soon (2007); Doloi et al. (2012)	Longer durations and resource conflicts	Layers 2a and 2b jointly
Material procurement delay	Sambasivan and Soon (2007); Zidane and Andersen (2018)	Late start of dependent activities	Layer 2b risk event; Layer 1 logic
Poor site management and planning	Chan and Kumaraswamy (1997); Doloi et al. (2012)	Logic errors, unrealistic durations	Layer 1 schedule quality
Unforeseen ground conditions	Chan and Kumaraswamy (1997)	Early-activity overruns on critical path	Layer 2b risk event
Slow approvals and inspections	Assaf and Al-Hejji (2006); Gündüz et al. (2013)	Waiting time between activities	Layer 2b risk event (lag)
Adverse weather	Gündüz et al. (2013); Durdyev and Hosseini (2020)	Correlated delays on exposed activities	Layer 2b correlated risk driver

3.5 Earned Value Management and Construction Forecasting

Earned value management derives SPI, CPI and the estimate at completion (EAC) from planned value (PV), earned value (EV) and actual cost (AC) (Fleming & Koppelman, 2010; Project Management Institute, 2017). Christensen (1993) found that cumulative CPI stabilises early, Anbari (2003) added time-based forecasts, and Lipke et al. (2009) applied statistical methods to earned schedule. Vandevor and Vanhoucke (2006) showed that classical SPI converges to unity late in a project regardless of delay, Vanhoucke and Vandevor (2007) linked forecast accuracy to network structure, and Kim and

Reinschmidt (2010) combined the Kalman filter with earned value. The baseline is always taken as given, a gap addressed in Section 7.4.

3.6 Float Ownership, Forensic Analysis and Contractual Time

Forensic schedule analysis attributes delay by comparing or modifying the baseline (AACE International, 2011a), so baseline quality determines the outcome of a claim. Kim and de la Garza (2005) showed that common resource-constrained algorithms can report float inconsistent with resource links, which Lu and Li (2003) addressed by recovering resource-dependent float. Galloway (2006) found that owners, contractors and designers disagree on who owns float, and on multi-contractor high-rise work overlapping work zones create competing claims on the same float (Obogo et al., 2019a). Layer 4 of the framework is therefore contractual as well as evaluative: a baseline that ignores resources is unfair to whichever party bears resource risk, typically the contractor under traditional procurement (Odeh & Battaineh, 2002).

3.7 Synthesis of Gaps

Table 3 summarises four gaps. The CPM stream treats float as a property of logic, whereas it depends on logic and resources jointly (Raz & Marshall, 1996). The risk stream computes criticality on networks that ignore resources, although resource links change criticality (Bowers, 1995). The delay stream ranks causes without locating them in the network (Durdyev & Hosseini, 2020). The earned value stream takes the baseline as outside its scope (Vandevoorde & Vanhoucke, 2006). Each gap is an interface between two framework layers, so the framework in Section 4 is organised around interfaces rather than techniques, and each interface becomes the location of a research proposition in Section 6.

Table 3. Thematic streams, constructs operationalised and integration gaps identified in the review

Stream	Representative studies	Constructs operationalised	Integration gap
CPM logic and float	Kelley and Walker (1959); Kelley (1961); Galloway (2006)	Network logic, ES/EF/LS/LF, TF, FF	Float assumed independent of resources
Resource-constrained scheduling and leveling	Wiest (1964); Kolisch (1996); Hegazy (1999); Lu and Li (2003)	Capacity, leveled duration, critical sequence	Deterministic durations; risk not modelled
Schedule risk and criticality	Van Slyke (1963); Dodin and Elmaghraby (1985); Hulett (2009)	Three-point estimates, CI, percentiles	Criticality computed without resources (except Bowers, 1995)
Delay causation	Assaf and Al-Hejji (2006); Doloi et al. (2012); Durdyev and Hosseini (2020)	Ranked delay causes	Causes not located in the network
Earned value and forecasting	Anbari (2003); Vandevoorde and Vanhoucke (2006); Lipke et al. (2009)	PV, EV, AC, SPI, CPI, EAC	Baseline treated as given
Float ownership and forensic analysis	AACE International (2011a); Kim and de la Garza (2005)	Entitlement, as-planned versus as-built	Resource effects on entitlement rarely modelled

4. The Risk-Based Project Delivery Framework

4.1 Framework Overview and Layer 1: Schedule Logic

The framework (Figure 1) arranges the constructs of Section 3 into four layers connected by six propositions. Layer 1, schedule logic, holds the work breakdown structure, the activity network with its relationships and lags, and the forward and backward pass outputs: early and late dates, total and free float, and the deterministic duration T_0 . It corresponds to classical CPM (Kelley, 1961) and the schedule model of the Practice Standard for Scheduling (Project Management Institute, 2019). Because missing relationships and excessive constraints are themselves sources of delay (Galloway, 2006), Layer 1 treats schedule quality checks as an explicit input, and it passes T_0 and a float profile to the later layers.

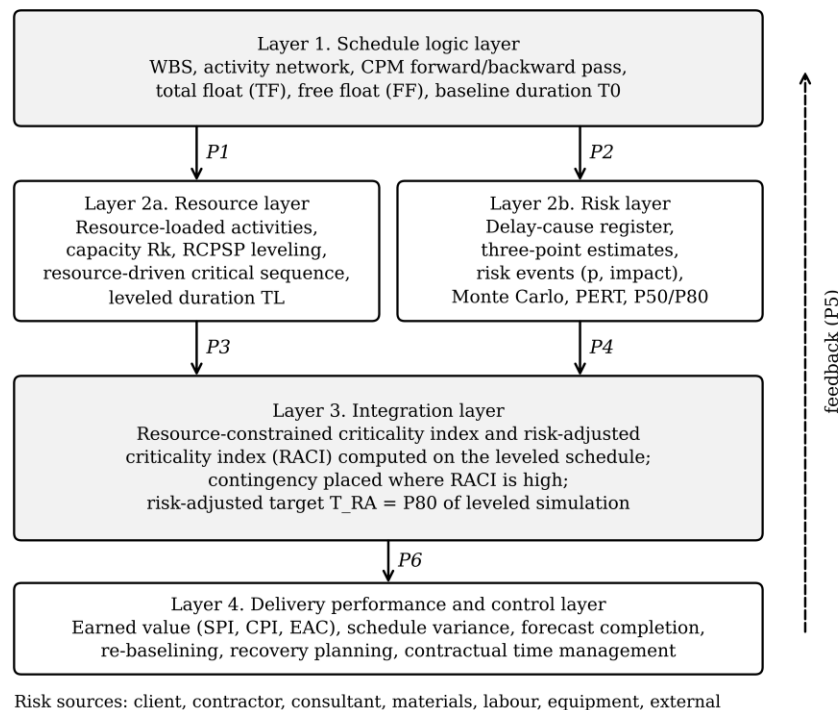


Figure 1. Risk-based project delivery framework linking schedule logic, resources, risk and delivery performance (P1 to P6 denote research propositions)

4.2 Layer 2: Resource and Risk Layers

Layer 2 has two parallel components. Layer 2a assigns resource demands and capacities and levels the schedule, producing duration TL and a resource-driven critical sequence (Wiest, 1964). Layer 2b translates the delay causes of Table 2 into three-point estimates and discrete risk events, following the risk-driver approach of Hulett (2009) and AACE International (2011b); risk-managed strategies for

regulated building developments (Ogbete et al., 2021) support keeping this register alongside the schedule. Gathering resource and risk information jointly follows Schatteman et al. (2008) and lets risk events act on resource availability, such as the productivity shortfalls ranked highly by Sambasivan and Soon (2007) and Doloi et al. (2012).

4.3 Layer 3: Integration Layer

Layer 3 is the core contribution of the framework. It simulates the leveled schedule rather than the unconstrained network, and it yields three outputs: a resource-constrained criticality index extending Bowers (1995); a risk-adjusted criticality index (RACI) that weights criticality by the normalised risk exposure of each activity's delay causes, answering the critique of Williams (1992) that criticality alone can misdirect management attention; and a risk-adjusted target duration T_{RA} , set at a percentile of the simulated completion distribution. The 80th percentile matches contingency practice (AACE International, 2011b) and the reference-class reasoning of Flyvbjerg (2014), which anchors forecasts to distributions of outcomes rather than single-point plans.

4.4 Layer 4: Delivery Performance and Control Layer

Layer 4 measures performance against the Layer 3 baseline using PV, EV, AC, SPI, CPI and EAC, with rules for recovery and re-baselining (Fleming & Koppelman, 2010). Its feedback arrow represents proposition P5: variances should update risk and resource assumptions, not only dates, as in the dynamic scheduling cycle of Vanhoucke (2013). Layer 4 also holds the contractual interface, because forensic methods measure delay against the accepted programme (AACE International, 2011a). In practice, each layer maps onto existing tools: logic and calendars, resource loading with a documented priority rule such as latest finish time (Kolisch, 1996), and a schedule risk tool (Hulett, 2009); the change is that leveling and risk analysis are completed before the baseline is frozen.

5. Model Formulation

5.1 Critical Path Equations

Consider a project represented as an activity-on-node network $G = (V, E)$, where $V = \{0, 1, \dots, n+1\}$ contains n real activities and dummy start and end nodes, and E contains finish-to-start precedence pairs. Each activity i has deterministic duration d_i , predecessor set $P(i)$ and successor set $S(i)$. Following Kelley (1961), the forward pass computes early start ES and early finish EF as shown in Equation (1).

$$ES_i = \max_{h \in P(i)} EF_h, \quad EF_i = ES_i + d_i \quad (1)$$

Here $ES_0 = 0$, and the deterministic baseline duration is $T0 = EF_{\{n+1\}}$. The backward pass, initialised with $LF_{\{n+1\}} = T0$, computes late finish LF and late start LS through Equation (2).

$$LF_i = \min_{j \in S(i)} LS_j, \quad LS_i = LF_i - d_i \quad (2)$$

Total float and free float then follow from Equations (3) and (4), where TF_i is the maximum delay of activity i that does not delay project completion and FF_i is the maximum delay that does not delay the early start of any successor. Activities with $TF_i = 0$ form the critical path in the unconstrained sense (Project Management Institute, 2019).

$$TF_i = LS_i - ES_i = LF_i - EF_i \quad (3)$$

$$FF_i = \min_{j \in S(i)} ES_j - EF_i \quad (4)$$

5.2 Resource-Constrained Scheduling and Leveling Objectives

Let K be the set of renewable resources, r_{ik} the per-period demand of activity i for resource k , and R_k the capacity of resource k . Decision variables are start times S_i . The RCPSP in the conceptual formulation of Brucker et al. (1999) minimises the start time of the dummy end activity, as shown in Equation (5), subject to precedence constraints in Equation (6) and resource constraints in Equation (7).

$$\min S_{n+1} \quad (5)$$

$$S_j \geq S_i + d_i, \quad \forall (i, j) \in E \quad (6)$$

$$\sum_{i \in A(t)} r_{ik} \leq R_k, \quad \forall k \in K, \forall t \quad (7)$$

In Equation (7), $A(t) = \{i : S_i \leq t < S_i + d_i\}$ is the set of activities in progress in period t . The optimum of Equation (5) is the resource-constrained duration $TL \geq T0$. With a fixed deadline, the leveling objective of Easa (1989) and El-Rayes and Jun (2009) replaces Equation (5) with Equation (8), the sum of squared daily usage u_{kt} .

$$\min \sum_{k \in K} \sum_{t=1}^T u_{kt}^2, \quad u_{kt} = \sum_{i \in A(t)} r_{ik} \quad (8)$$

Because the RCPSP is strongly NP-hard (Blazewicz et al., 1983), the illustrative application uses a serial schedule generation scheme with a latest-finish-time priority rule, a combination that Kolisch (1996) showed to be robust and that resembles the leveling logic of commercial scheduling tools.

5.3 Probabilistic Durations and Risk-Adjusted Criticality

For each activity, an optimistic estimate a_i , most likely estimate m_i and pessimistic estimate b_i are elicited. Under classical PERT assumptions (Malcolm et al., 1959), the expected duration and variance are given by Equation (9).

$$t_{e,i} = \frac{a_i + 4m_i + b_i}{6}, \quad \sigma_i^2 = \left(\frac{b_i - a_i}{6}\right)^2 \quad (9)$$

Each activity also carries a discrete risk event with probability p_i and impact δ_i from Table 2. In replication s of N , sampled durations $d_i(s)$ yield a resource-constrained schedule with governing chain $C(s)$, and the resource-constrained criticality index is given by Equation (10), where $I[\cdot]$ is the indicator function. It reduces to the index of Van Slyke (1963) when resources are slack and matches Bowers (1995) when they bind.

$$CI_i^{RC} = \frac{1}{N} \sum_{s=1}^N I[i \in C(s)] \quad (10)$$

The normalised risk exposure of activity i is defined in Equation (11), so that $0 \leq R_i \leq 1$ and the most exposed activity has $R_i = 1$. This exposure term is new to this study and operationalises the probability-impact logic of construction risk assessment (Al-Bahar & Crandall, 1990; Zou et al., 2007).

$$R_i = \frac{p_i \delta_i}{\max_j (p_j \delta_j)} \quad (11)$$

The risk-adjusted criticality index is given in Equation (12), where $\lambda \geq 0$ is a policy weight. With $\lambda = 0$ it equals the resource-constrained index; with $\lambda = 1$ an always-critical activity scores 1 if maximally exposed and 0.5 if exposure is negligible, separating criticality from impact as Williams (1992) and Elmaghraby (2000) recommend.

$$RACI_i = CI_i^{RC} \cdot \frac{1 + \lambda R_i}{1 + \lambda} \quad (12)$$

5.4 Performance Measurement and Risk-Adjusted Targets

Earned value indices at status date t are defined in Equation (13), and the CPI-based estimate at completion is given in Equation (14), where BAC is the budget at completion (Fleming & Koppelman, 2010; Christensen, 1993).

$$SPI(t) = \frac{EV(t)}{PV(t)}, \quad CPI(t) = \frac{EV(t)}{AC(t)} \quad (13)$$

$$EAC = \frac{BAC}{CPI} \quad (14)$$

Finally, the risk-adjusted target duration is the q -quantile of the simulated resource-constrained completion time T^{RC} , as expressed in Equation (15), where F is the empirical cumulative distribution function and $q = 0.80$ is used here. The schedule contingency is then $T_{RA} - TL$, which can be held as a project buffer in the sense discussed by Herroelen and Leus (2001) in their assessment of critical chain scheduling.

$$T_{RA} = F_{T^{RC}}^{-1}(q) \quad (15)$$

5.5 Computational Procedure

The procedure has five steps. Step 1 applies Equations (1) to (4) to obtain T_0 , float and the CPM critical path. Step 2 applies a serial schedule generation scheme with latest-finish priority subject to Equations (6) and (7), giving TL and the profile for Equation (8). Step 3 samples triangular durations from a_i , m_i and b_i , adds δ_i with probability p_i , and repeats Steps 1 and 2 N times. Step 4 traces each replication's governing chain backward from the last-finishing activity through predecessors or resource-blocking activities to accumulate Equation (10). Step 5 computes Equations (11), (12) and (15), and Equations (13) and (14) at the status date. Triangular distributions are standard in construction schedule risk practice (AACE International, 2011b; Hulett, 2009).

6. Research Propositions and Validation Protocol

6.1 Research Propositions

Six propositions follow, each an arrow in Figure 1. P1: TL exceeds T_0 , increasingly with the peak-to-capacity ratio (Wiest, 1964; Davis & Patterson, 1975). P2: Delay causes acting through resource availability affect completion more than comparable causes acting on isolated activities (Raz & Marshall, 1996; Sambasivan & Soon, 2007). P3: Activities with positive CPM float but high resource-constrained criticality are over-represented among overrun drivers (Bowers, 1995; Lu & Li, 2003). P4: Deterministic baselines understate median completion, more so under resource constraints (MacCrimmon & Ryavec, 1964; Hulett, 2009). P5: Updating risk and resource assumptions in response to variances reduces final overrun compared with updating dates only (Vanhoucke, 2013). P6: SPI at a status date depends materially on the baseline chosen (Vandevoorde & Vanhoucke, 2006).

6.2 Validation Protocol

Table 4 sets out the measurement and test for each proposition. Archival testing reconstructs TL , T_0 , criticality and SPI under alternative baselines from native schedule files with updates and as-built dates, as in forensic reconstruction (AACE International, 2011a). Simulation testing adapts PSPLIB networks

(Kolisch & Sprecher, 1997) to building activities, with risk registers parameterised from delay surveys such as Gündüz et al. (2013). Structured expert review of the framework layers with planners and project controls managers would complement both routes, using the construct definitions in Section 5 as the interview protocol, and archival samples should support mixed-effects models with project as a random effect, since activities are nested in projects.

Table 4. Validation protocol for the research propositions

P	Constructs	Measurement	Recommended test
P1	T0, TL, peak-to-capacity ratio	Reconstruct CPM and leveled durations from native schedule files	Paired comparison; regression of (TL - T0)/T0 on peak-to-capacity ratio
P2	Delay mechanism (resource versus activity), completion impact	Classify as-built delay events by mechanism using the delay-cause mapping of Section 3.4	Mixed-effects model with project random effect
P3	CPM float, resource-constrained CI, overrun contribution	Simulated CI on leveled baseline; forensic attribution of overrun	Logistic regression of overrun-driving status on CI and float
P4	Deterministic duration, simulated P50, actual duration	Compare baseline, P50 and as-built completion	Calibration test of percentile forecasts against outcomes
P5	Update practice, final overrun	Code update records (dates only versus risk and resource revision)	Propensity-matched comparison of final overrun
P6	Baseline type, reported SPI	Recompute SPI at fixed status dates under alternative baselines	Within-project repeated-measures comparison

7. Illustrative Application

7.1 Scenario Definition

The illustrative scenario is a synthetic two-storey reinforced concrete office building of about 1,200 square metres. Its thirteen activities share one pooled resource, site trade labour, with a capacity of 10 workers at 250 currency units per worker-day, giving a labour budget of 132,250 units (Table 5). Risk events carry delay causes from Table 2 with probabilities of 0.10 to 0.30 and impacts of 2 to 4 days, consistent with Assaf and Al-Hejji (2006) and Doloi et al. (2012). CPM passes, a serial scheme with latest-finish priority (Kolisch, 1996), 10,000 Monte Carlo replications and earned value calculations were run in Python with a fixed random seed so that the results are reproducible. The scenario is representative in structure and parameter ranges rather than a description of an actual project.

Table 5. Illustrative building project: activity data, labour demand, three-point estimates and assigned risk events (synthetic scenario)

ID	Activity	d (days)	Pred.	Workers	a / m / b (days)	p / δ (days)	Assigned delay cause
A	Site mobilisation and excavation	5	-	4	4 / 5 / 8	0.20 / 3	Unforeseen ground conditions

ID	Activity	d (days)	Pred.	Workers	a / m / b (days)	p / δ (days)	Assigned delay cause
B	Foundations	8	A	6	7 / 8 / 12	0.15 / 3	Inspection and approval delay
C	Ground-floor slab	6	B	5	5 / 6 / 9	0.10 / 2	Concrete supply interruption
D	Structural frame	12	C	8	10 / 12 / 17	0.25 / 4	Rebar and formwork shortage
E	Roof structure	7	D	6	6 / 7 / 10	0.15 / 2	Adverse weather
F	External envelope (blockwork)	10	D	7	9 / 10 / 14	0.20 / 3	Labour productivity shortfall
G	MEP rough-in	9	D	5	8 / 9 / 14	0.30 / 4	Design change orders
H	Windows and doors	5	F	3	4 / 5 / 8	0.25 / 3	Late procurement of materials
I	Roofing and waterproofing	4	E	4	3 / 4 / 6	0.15 / 2	Adverse weather
J	Internal partitions and plaster	8	G,H	6	7 / 8 / 11	0.15 / 2	Subcontractor coordination
K	Finishes (flooring, painting)	9	J,I	7	8 / 9 / 13	0.20 / 3	Owner-driven finish changes
L	External works	6	F	4	5 / 6 / 9	0.10 / 2	Utility connection delay
M	Testing, commissioning, handover	4	K,L	3	3 / 4 / 7	0.20 / 2	Authority sign-off delay

7.2 Baseline and Resource-Leveled Schedules

CPM gives $T_0 = 67$ days on critical path A-B-C-D-F-H-J-K-M, with 6 days of float on G (MEP rough-in), 12 on E and I, and 16 on L (Table 6). The early-start schedule peaks at 18 workers between days 31 and 37, when roof, envelope and MEP rough-in all follow the frame, exceeding capacity on 70 worker-days. Leveling delays E, G, I and L and, through resource links, J, K and M, giving $TL = 78$ days (16.4 percent longer). Figure 2 shows that the peak falls to 10 workers, the sum of squared daily usage by 28.3 percent and day-to-day crew changes from 46 to 34. This supports P1 and the finding of Wiest (1964) that resource links create a critical sequence different from the CPM path.

Table 6. CPM, resource-leveled and risk-adjusted results by activity (capacity 10 workers; 10,000 replications)

ID	ES	EF	TF	FF	Leveled start	Shift (days)	CI (CPM)	CI (resource-constrained)	R	RACI ($\lambda = 1$)
A	0	5	0	0	0	0	1.000	1.000	0.500	0.750
B	5	13	0	0	5	0	1.000	1.000	0.375	0.688
C	13	19	0	0	13	0	1.000	1.000	0.167	0.583
D	19	31	0	0	19	0	1.000	1.000	0.833	0.917
E	31	38	12	0	50	19	0.000	1.000	0.250	0.625
F	31	41	0	0	31	0	0.981	1.000	0.500	0.750
G	31	40	6	6	41	10	0.019	1.000	1.000	1.000

ID	ES	EF	TF	FF	Leveled start	Shift (days)	CI (CPM)	CI (resource-constrained)	R	RACI ($\lambda = 1$)
H	41	46	0	0	41	0	0.981	0.134	0.625	0.109
I	38	42	12	12	57	19	0.000	0.005	0.250	0.003
J	46	54	0	0	57	11	1.000	1.000	0.250	0.625
K	54	63	0	0	65	11	1.000	1.000	0.500	0.750
L	41	47	16	16	46	5	0.000	0.124	0.167	0.072
M	63	67	0	0	74	11	1.000	1.000	0.333	0.667

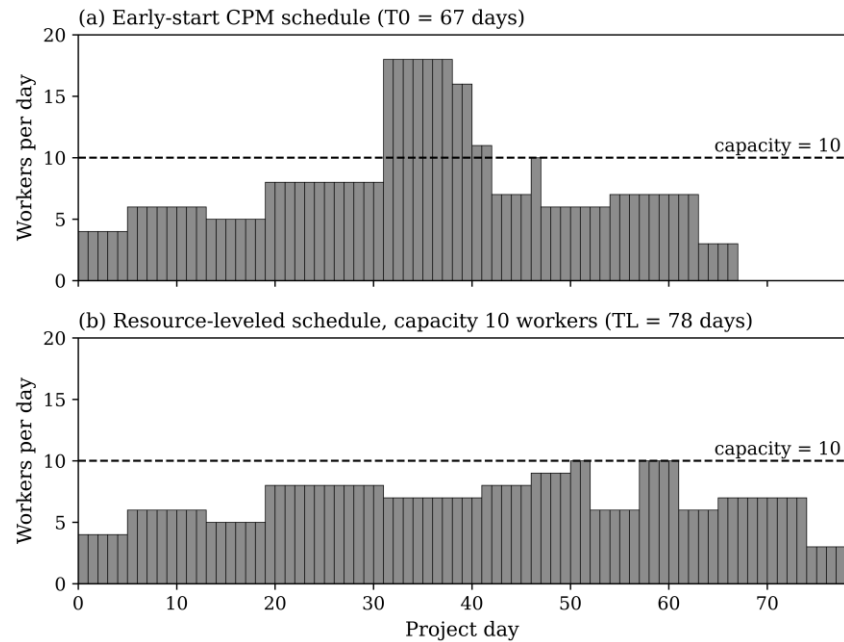


Figure 2. Daily labour histograms for the illustrative project: (a) early-start CPM schedule; (b) resource-leveled schedule at a capacity of 10 workers

7.3 Risk-Adjusted Schedule and Criticality

PERT gives an expected duration of 70.7 days (standard deviation 2.38), a 6.2 percent chance of meeting T0. Simulating the unconstrained network gives P50, P80 and P90 of 78.9, 83.0 and 85.1 days, reflecting merge-event bias (MacCrimmon & Ryavec, 1964) and discrete risk events. Simulating the leveled schedule raises these to 92, 97 and 99 days (Figure 3). With $q = 0.80$, $T_{RA} = 97$ days, a contingency of 19 days over TL and 30 over T0, and the probability of finishing within 78 days is 0.07 percent, supporting P4 and the warning of Hulett (2009) against treating a deterministic resource-loaded schedule as a commitment date.

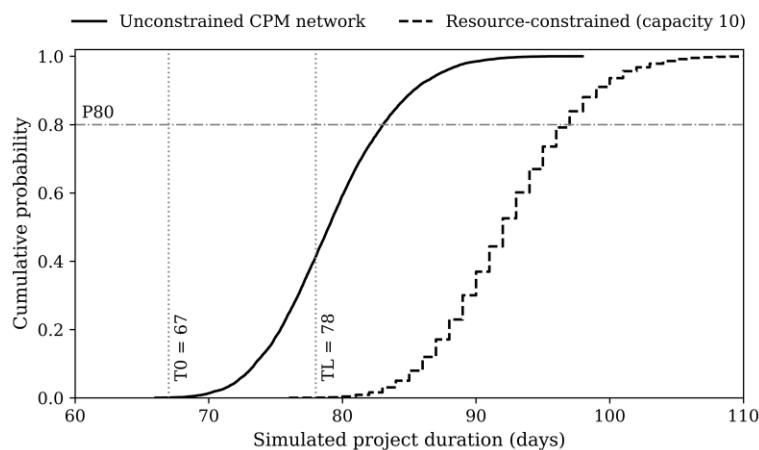


Figure 3. Cumulative distribution of simulated completion time for the unconstrained CPM network and the resource-constrained schedule (10,000 replications)

Criticality changes more than duration (Table 6). Activities E and G score 0.000 and 0.019 in the unconstrained network but 1.000 once leveled, while H (windows and doors) falls from 0.981 to 0.134. RACI with $\lambda = 1$ ranks G first (1.000), then D (0.917) and A, F and K (0.750), with H at 0.109. Risk response for MEP design changes and for frame rebar and formwork supply should therefore precede window procurement, reversing the unconstrained ranking, which supports P3 and turns the argument of Bowers (1995) and Raz and Marshall (1996) into a decision rule.

7.4 Earned Value Under Alternative Baselines

For P6, an as-performed case was simulated with overruns of 4 days on the frame and MEP rough-in, 3 on windows and doors and 1 on mobilisation, finishing on day 87. At day 40, EV is 55,500 and AC 64,500 units. Against the leveled baseline (PV 64,250), SPI is 0.864, CPI 0.860 and EAC 153,696 units against a budget of 132,250. Against the early-start baseline (PV 88,000), SPI is 0.631, and against a 93-day risk-adjusted baseline built from mean durations plus expected risk impacts (PV 54,333), SPI is 1.021. The 39-point spread comes entirely from baseline choice (Table 7), confirming Vandevoorde and Vanhoucke (2006) and Lipke et al. (2009) that schedule indicators must be read against their baseline.

Table 7. Comparison of baseline, resource-leveled and risk-adjusted schedule states for the illustrative project

Measure	Early-start CPM	Resource-leveled	Risk-adjusted (leveled, simulated)
Deterministic duration (days)	67	78	93 (expected-value durations)
Peak labour demand (workers)	18	10	10
Worker-days above capacity	70	0	0

Measure	Early-start CPM	Resource-leveled	Risk-adjusted (leveled, simulated)
Sum of squared daily usage	5,333	3,821	not applicable
Simulated P50 completion (days)	78.9	92	92
Simulated P80 completion (days)	83.0	97	97 (T_RA)
Probability of meeting deterministic duration	0.04%	0.07%	80% by construction of T_RA
Planned value at day 40 (units)	88,000	64,250	54,333
SPI at day 40 (EV = 55,500)	0.631	0.864	1.021
CPI at day 40 (AC = 64,500)	0.860	0.860	0.860

7.5 Sensitivity to Resource Capacity

Capacity was varied from 8 to 18 workers (4,000 replications each; Table 8). At 12 workers or more, leveling fits within float, TL is 67 days and P80 stabilises at 83 days, so the residual gap is due to risk alone. At 11 and 10 workers, TL rises to 74 and 78 days and P80 to 91 and 97 days; at 9 or fewer, the frame cannot overlap any other trade, TL reaches 88 days and P80 exceeds 105 days. Consistent with the resource-strength parameters of Kolisch and Sprecher (1997), the resource-risk interaction is concentrated near peak unconstrained demand: moving from 10 to 12 workers removes 14 days from P80, while moving from 12 to 18 removes none, supporting the joint evaluation of allocation and leveling advocated by Hegazy (1999).

Table 8. Sensitivity of leveled and simulated completion to labour capacity (4,000 replications per setting)

Capacity (workers)	Leveled duration TL (days)	Simulated P50 (days)	Simulated P80 (days)
8	88	103	108
9	88	101	106
10	78	92	97
11	74	87	91
12	67	79	83
14	67	79	83
18	67	79	83

8. Discussion

8.1 Theoretical Contribution

The study treats float and criticality as properties of the joint logic-resource-risk system. CPM defines float on the network (Kelley, 1961), RCPSP research shows that resources alter durations (Wiest, 1964; Hartmann & Briskorn, 2010), and stochastic research shows that uncertainty alters criticality (Van Slyke, 1963; Elmaghraby, 2000). Equation (12) combines the three, and the illustration shows that this changes management priorities, not merely values. Assigning each delay cause to the construct through which it

acts turns a ranking exercise into a modelling input, answering the observation of Durdyev and Hosseini (2020) that delay lists have outpaced explanations and locating where uncertainty enters the schedule in the sense of Ward and Chapman (2003).

8.2 Comparison with Prior Work

The effect sizes match prior evidence. The 16.4 percent extension lies within the range of priority-rule benchmarks (Davis & Patterson, 1975; Kolisch, 1996), the PERT-to-simulation gap matches MacCrimmon and Ryavec (1964) and Hulett (2009), and the criticality reversal for E, G and H mirrors Raz and Marshall (1996) and Lu and Li (2003). The new finding is that these effects compound to a target 30 days beyond T0, and that baseline choice shifts SPI by 39 points, extending Vandevoorde and Vanhoucke (2006) and Vanhoucke and Vandevoorde (2007), who held the baseline fixed. Unlike Schatteman et al. (2008), it emphasises diagnosis rather than buffer insertion.

8.3 Boundary Conditions and Interpretation

Three conditions bound the framework. Resources must constrain part of the project, otherwise it reduces to conventional schedule risk analysis (Section 7.5). Risks must be attached to activities or resources, which project-level registers typical of survey studies cannot do (Durdyev & Hosseini, 2020). Simulation must respect resource constraints in every replication, which schedule generation schemes do fast enough for practical networks (Kolisch & Hartmann, 2006). RACI is a ranking device rather than an estimate of delay contribution, which would require the sensitivity measures of Elmaghraby (2000), and recomputing it at each update links it to the control cycle of Vanhoucke (2013).

9. Implications for Practice and Policy

Planners should level schedules before baselining them, a step applied inconsistently (Galloway, 2006). Controls teams should report SPI with its baseline and prefer the time-based measures of Anbari (2003) and Lipke et al. (2009) late in a project, and risk managers can compute RACI from any resource-respecting Monte Carlo tool (AACE International, 2011b). For owners and public agencies, the gap between T0 and T_RA implies that tender durations from unconstrained networks are optimistic (Flyvbjerg et al., 2002), and delivery models allocate this risk differently (Aminu-Ibrahim et al., 2019). Tender schedules should be resource-loaded with a stated confidence level, and claims assessed against the leveled programme (AACE International, 2011a). The PMBOK Guide (Project Management Institute, 2017) and the Practice Standard for Scheduling (Project Management Institute, 2019) should present logic,

resources and risk, integration and control as one sequence, and use Table 2 to attach common causes (Assaf & Al-Hejji, 2006; Zidane & Andersen, 2018) to specific activities.

10. Limitations and Future Research

The review covered three databases and English-language sources to 2021, so studies in other languages may be missed (Tranfield et al., 2003). The illustration uses one synthetic network with one pooled resource, and real projects with several trades, calendars and lags may amplify or dampen the effects. Durations were sampled independently, whereas correlated durations widen the distribution (Ökmen & Öztaş, 2008). A single-rule serial scheme does not guarantee an optimal TL, and metaheuristics (Pellerin et al., 2020) may shorten it. The weight λ was not calibrated. Future work should test P1 to P6 on archival schedules, calibrate λ , extend the model to multi-resource and multi-mode settings (Hartmann & Briskorn, 2010), and test whether probabilistic forecasting (Kim & Reinschmidt, 2010) improves with a risk-adjusted baseline.

11. Conclusion

This study integrated critical path scheduling, resource optimisation, construction risk and delivery performance for building projects. The four-layer framework addresses the interfaces between these previously separate streams: schedule logic supplies the network, resource and risk layers modify it in parallel, the integration layer computes resource-constrained, risk-adjusted criticality and a percentile target duration, and the delivery layer measures performance against an explicitly chosen baseline. Fifteen equations formalise the framework and six propositions make it testable.

In the illustration, leveling to 10 workers extended the duration from 67 to 78 days, the 80th percentile completion reached 97 days, and the risk-adjusted index prioritised different activities from an unconstrained analysis. The same progress gave an SPI of 0.631, 0.864 or 1.021 depending on the baseline. Float, criticality and performance indices are only as meaningful as their baseline, which should be resource-feasible and risk-informed before it is used to commit, control or claim.

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Conflict of interest

The authors declare no conflict of interest.

Data availability

All data used in the illustrative application are synthetic and are reported in full in Tables 5 to 8 of this article. No other data were generated or analysed.

Author contributions

Susan Ochi Makut: conceptualization, scheduling and risk framework design, writing (original draft).
Adedoyin Oluwatoyin Olutimehin: methodology, formal analysis, visualization, writing (original draft).
Adeshola Oladunni Bankole: literature review, validation, writing (review and editing).

References

1. AACE International. (2011a). *Forensic schedule analysis* (Recommended Practice No. 29R-03). AACE International.
2. AACE International. (2011b). *Integrated cost and schedule risk analysis using Monte Carlo simulation of a CPM model* (Recommended Practice No. 57R-09). AACE International.
3. Agbabiaka, J., Okonkwo, C. S., Ogunwole, O., Mayo, W., & Okeke, O. T. (2019). Supply chain risk management model for EPC and gas processing projects. *Iconic Research and Engineering Journals*, 3(2), 968-980. <https://doi.org/10.64388/IREV3I2-1713124>
4. Aibinu, A. A., & Jagboro, G. O. (2002). The effects of construction delays on project delivery in Nigerian construction industry. *International Journal of Project Management*, 20(8), 593-599. [https://doi.org/10.1016/S0263-7863\(02\)00028-5](https://doi.org/10.1016/S0263-7863(02)00028-5)
5. Al-Bahar, J. F., & Crandall, K. C. (1990). Systematic risk management approach for construction projects. *Journal of Construction Engineering and Management*, 116(3), 533-546. [https://doi.org/10.1061/\(ASCE\)0733-9364\(1990\)116:3\(533\)](https://doi.org/10.1061/(ASCE)0733-9364(1990)116:3(533))
6. Aminu-Ibrahim, A. Y., Ogbete, J. C., & Ambali, K. B. (2019). Capital project delivery models for high risk healthcare infrastructure in developing national health systems. *Iconic Research and Engineering Journals*, 2(10), 626-649. <https://doi.org/10.64388/IREV2I10-1713588>
7. Anbari, F. T. (2003). Earned value project management method and extensions. *Project Management Journal*, 34(4), 12-23.
8. Assaf, S. A., & Al-Hejji, S. (2006). Causes of delay in large construction projects. *International Journal of Project Management*, 24(4), 349-357. <https://doi.org/10.1016/j.ijproman.2005.11.010>

9. Blazewicz, J., Lenstra, J. K., & Rinnooy Kan, A. H. G. (1983). Scheduling subject to resource constraints: Classification and complexity. *Discrete Applied Mathematics*, 5(1), 11-24.
10. Bowers, J. A. (1995). Criticality in resource constrained networks. *Journal of the Operational Research Society*, 46(1), 80-91. <https://doi.org/10.1057/jors.1995.9>
11. Brucker, P., Drexl, A., Möhring, R., Neumann, K., & Pesch, E. (1999). Resource-constrained project scheduling: Notation, classification, models, and methods. *European Journal of Operational Research*, 112(1), 3-41. [https://doi.org/10.1016/S0377-2217\(98\)00204-5](https://doi.org/10.1016/S0377-2217(98)00204-5)
12. Chan, D. W. M., & Kumaraswamy, M. M. (1997). A comparative study of causes of time overruns in Hong Kong construction projects. *International Journal of Project Management*, 15(1), 55-63.
13. Chan, W. T., Chua, D. K. H., & Kannan, G. (1996). Construction resource scheduling with genetic algorithms. *Journal of Construction Engineering and Management*, 122(2), 125-132. [https://doi.org/10.1061/\(ASCE\)0733-9364\(1996\)122:2\(125\)](https://doi.org/10.1061/(ASCE)0733-9364(1996)122:2(125))
14. Christensen, D. S. (1993). The estimate at completion problem: A review of three studies. *Project Management Journal*, 24(1), 37-42.
15. Davis, E. W., & Patterson, J. H. (1975). A comparison of heuristic and optimum solutions in resource-constrained project scheduling. *Management Science*, 21(8), 944-955. <https://doi.org/10.1287/mnsc.21.8.944>
16. Demeulemeester, E. L., & Herroelen, W. S. (2002). *Project scheduling: A research handbook*. Kluwer Academic Publishers. <https://doi.org/10.1007/b101924>
17. Dodin, B. M., & Elmaghraby, S. E. (1985). Approximating the criticality indices of the activities in PERT networks. *Management Science*, 31(2), 207-223. <https://doi.org/10.1287/mnsc.31.2.207>
18. Doloi, H., Sawhney, A., Iyer, K. C., & Rentala, S. (2012). Analysing factors affecting delays in Indian construction projects. *International Journal of Project Management*, 30(4), 479-489. <https://doi.org/10.1016/j.ijproman.2011.10.004>
19. Durdyev, S., & Hosseini, M. R. (2020). Causes of delays on construction projects: A comprehensive list. *International Journal of Managing Projects in Business*, 13(1), 20-46. <https://doi.org/10.1108/IJMPB-09-2018-0178>
20. Easa, S. M. (1989). Resource leveling in construction by optimization. *Journal of Construction Engineering and Management*, 115(2), 302-316. [https://doi.org/10.1061/\(ASCE\)0733-9364\(1989\)115:2\(302\)](https://doi.org/10.1061/(ASCE)0733-9364(1989)115:2(302))

21. El-Rayes, K., & Jun, D. H. (2009). Optimizing resource leveling in construction projects. *Journal of Construction Engineering and Management*, 135(11), 1172-1180. [https://doi.org/10.1061/\(ASCE\)CO.1943-7862.0000097](https://doi.org/10.1061/(ASCE)CO.1943-7862.0000097)
22. Elmaghraby, S. E. (2000). On criticality and sensitivity in activity networks. *European Journal of Operational Research*, 127(2), 220-238. [https://doi.org/10.1016/S0377-2217\(99\)00483-X](https://doi.org/10.1016/S0377-2217(99)00483-X)
23. Fleming, Q. W., & Koppelman, J. M. (2010). *Earned value project management* (4th ed.). Project Management Institute.
24. Flyvbjerg, B. (2014). What you should know about megaprojects and why: An overview. *Project Management Journal*, 45(2), 6-19. <https://doi.org/10.1002/pmj.21409>
25. Flyvbjerg, B., Holm, M. S., & Buhl, S. (2002). Underestimating costs in public works projects: Error or lie? *Journal of the American Planning Association*, 68(3), 279-295.
26. Frimpong, Y., Oluwoye, J., & Crawford, L. (2003). Causes of delay and cost overruns in construction of groundwater projects in a developing countries; Ghana as a case study. *International Journal of Project Management*, 21(5), 321-326.
27. Galloway, P. D. (2006). Survey of the construction industry relative to the use of CPM scheduling for construction projects. *Journal of Construction Engineering and Management*, 132(7), 697-711. [https://doi.org/10.1061/\(ASCE\)0733-9364\(2006\)132:7\(697\)](https://doi.org/10.1061/(ASCE)0733-9364(2006)132:7(697))
28. Gündüz, M., Nielsen, Y., & Özdemir, M. (2013). Quantification of delay factors using the relative importance index method for construction projects in Turkey. *Journal of Management in Engineering*, 29(2), 133-139. [https://doi.org/10.1061/\(ASCE\)ME.1943-5479.0000129](https://doi.org/10.1061/(ASCE)ME.1943-5479.0000129)
29. Harris, R. B. (1990). Packing method for resource leveling (PACK). *Journal of Construction Engineering and Management*, 116(2), 331-350.
30. Hartmann, S., & Briskorn, D. (2010). A survey of variants and extensions of the resource-constrained project scheduling problem. *European Journal of Operational Research*, 207(1), 1-14. <https://doi.org/10.1016/j.ejor.2009.11.005>
31. Hartmann, S., & Kolisch, R. (2000). Experimental evaluation of state-of-the-art heuristics for the resource-constrained project scheduling problem. *European Journal of Operational Research*, 127(2), 394-407. [https://doi.org/10.1016/S0377-2217\(99\)00485-3](https://doi.org/10.1016/S0377-2217(99)00485-3)
32. Hegazy, T. (1999). Optimization of resource allocation and leveling using genetic algorithms. *Journal of Construction Engineering and Management*, 125(3), 167-175. [https://doi.org/10.1061/\(ASCE\)0733-9364\(1999\)125:3\(167\)](https://doi.org/10.1061/(ASCE)0733-9364(1999)125:3(167))

33. Herroelen, W., De Reyck, B., & Demeulemeester, E. (1998). Resource-constrained project scheduling: A survey of recent developments. *Computers & Operations Research*, 25(4), 279-302. [https://doi.org/10.1016/S0305-0548\(97\)00055-5](https://doi.org/10.1016/S0305-0548(97)00055-5)
34. Herroelen, W., & Leus, R. (2001). On the merits and pitfalls of critical chain scheduling. *Journal of Operations Management*, 19(5), 559-577.
35. Herroelen, W., & Leus, R. (2005). Project scheduling under uncertainty: Survey and research potentials. *European Journal of Operational Research*, 165(2), 289-306. <https://doi.org/10.1016/j.ejor.2004.04.002>
36. Hulett, D. (2009). *Practical schedule risk analysis*. Gower.
37. Kelley, J. E. (1961). Critical-path planning and scheduling: Mathematical basis. *Operations Research*, 9(3), 296-320. <https://doi.org/10.1287/opre.9.3.296>
38. Kelley, J. E., & Walker, M. R. (1959). Critical-path planning and scheduling. In *Papers presented at the December 1-3, 1959, Eastern Joint IRE-AIEE-ACM Computer Conference* (pp. 160-173). Association for Computing Machinery. <https://doi.org/10.1145/1460299.1460318>
39. Kim, B. C., & Reinschmidt, K. F. (2010). Probabilistic forecasting of project duration using Kalman filter and the earned value method. *Journal of Construction Engineering and Management*, 136(8), 834-843. [https://doi.org/10.1061/\(ASCE\)CO.1943-7862.0000192](https://doi.org/10.1061/(ASCE)CO.1943-7862.0000192)
40. Kim, K., & de la Garza, J. M. (2005). Evaluation of the resource-constrained critical path method algorithms. *Journal of Construction Engineering and Management*, 131(5), 522-532. [https://doi.org/10.1061/\(ASCE\)0733-9364\(2005\)131:5\(522\)](https://doi.org/10.1061/(ASCE)0733-9364(2005)131:5(522))
41. Kolisch, R. (1996). Serial and parallel resource-constrained project scheduling methods revisited: Theory and computation. *European Journal of Operational Research*, 90(2), 320-333. [https://doi.org/10.1016/0377-2217\(95\)00357-6](https://doi.org/10.1016/0377-2217(95)00357-6)
42. Kolisch, R., & Hartmann, S. (2006). Experimental investigation of heuristics for resource-constrained project scheduling: An update. *European Journal of Operational Research*, 174(1), 23-37. <https://doi.org/10.1016/j.ejor.2005.01.065>
43. Kolisch, R., & Sprecher, A. (1997). PSPLIB: A project scheduling problem library. *European Journal of Operational Research*, 96(1), 205-216. [https://doi.org/10.1016/S0377-2217\(96\)00170-1](https://doi.org/10.1016/S0377-2217(96)00170-1)
44. Lipke, W., Zwikael, O., Henderson, K., & Anbari, F. (2009). Prediction of project outcome: The application of statistical methods to earned value management and earned schedule performance

- indexes. *International Journal of Project Management*, 27(4), 400-407. <https://doi.org/10.1016/j.ijproman.2008.02.009>
45. Lu, M., & Li, H. (2003). Resource-activity critical-path method for construction planning. *Journal of Construction Engineering and Management*, 129(4), 412-420. [https://doi.org/10.1061/\(ASCE\)0733-9364\(2003\)129:4\(412\)](https://doi.org/10.1061/(ASCE)0733-9364(2003)129:4(412))
46. MacCrimmon, K. R., & Ryavec, C. A. (1964). An analytical study of the PERT assumptions. *Operations Research*, 12(1), 16-37. <https://doi.org/10.1287/opre.12.1.16>
47. Malcolm, D. G., Roseboom, J. H., Clark, C. E., & Fazar, W. (1959). Application of a technique for research and development program evaluation. *Operations Research*, 7(5), 646-669. <https://doi.org/10.1287/opre.7.5.646>
48. Moher, D., Liberati, A., Tetzlaff, J., Altman, D. G., & The PRISMA Group. (2009). Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement. *PLoS Medicine*, 6(7), e1000097. <https://doi.org/10.1371/journal.pmed.1000097>
49. Mulholland, B., & Christian, J. (1999). Risk assessment in construction schedules. *Journal of Construction Engineering and Management*, 125(1), 8-15. [https://doi.org/10.1061/\(ASCE\)0733-9364\(1999\)125:1\(8\)](https://doi.org/10.1061/(ASCE)0733-9364(1999)125:1(8))
50. Nwafor, M. I., Uduokhai, D. O., Stephen, G.-O. I. D., & Aransi, A. N. (2019). Developing an analytical framework for enhancing efficiency in public infrastructure delivery systems. *Iconic Research and Engineering Journals*, 2(11), 657-670. <https://doi.org/10.64388/IREV2I11-1712239>
51. Obogo, S. F., Ozobu, C. O., & Uduokhai, D. O. (2019a). Development of a construction safety risk governance model for multi contractor high rise projects. *Iconic Research and Engineering Journals*, 2(9), 502-522. <https://doi.org/10.64388/IREV2I9-1715495>
52. Obogo, S. F., Uduokhai, D. O., & Ozobu, C. O. (2019b). Systematic review of hazard identification and risk control practices in urban construction projects. *Iconic Research and Engineering Journals*, 2(12), 666-681. <https://doi.org/10.64388/IREV2I12-1715496>
53. Odeh, A. M., & Battaineh, H. T. (2002). Causes of construction delay: Traditional contracts. *International Journal of Project Management*, 20(1), 67-73. [https://doi.org/10.1016/S0263-7863\(00\)00037-5](https://doi.org/10.1016/S0263-7863(00)00037-5)
54. Ogbete, J. C., Aminu-Ibrahim, A. Y., & Ambali, K. B. (2021). Risk managed construction strategies for complex and highly regulated healthcare facility developments. *International Journal of Scientific*

- Research in Computer Science, Engineering and Information Technology*, 7(5), 362-392.
<https://doi.org/10.32628/CSEIT217561>
55. Ökmen, Ö., & Öztaş, A. (2008). Construction project network evaluation with correlated schedule risk analysis model. *Journal of Construction Engineering and Management*, 134(1), 49-63.
[https://doi.org/10.1061/\(ASCE\)0733-9364\(2008\)134:1\(49\)](https://doi.org/10.1061/(ASCE)0733-9364(2008)134:1(49))
56. Pellerin, R., Perrier, N., & Berthaut, F. (2020). A survey of hybrid metaheuristics for the resource-constrained project scheduling problem. *European Journal of Operational Research*, 280(2), 395-416.
<https://doi.org/10.1016/j.ejor.2019.01.063>
57. Pritsker, A. A. B., Watters, L. J., & Wolfe, P. M. (1969). Multiproject scheduling with limited resources: A zero-one programming approach. *Management Science*, 16(1), 93-108.
<https://doi.org/10.1287/mnsc.16.1.93>
58. Project Management Institute. (2017). *A guide to the project management body of knowledge (PMBOK guide)* (6th ed.). Project Management Institute.
59. Project Management Institute. (2019). *Practice standard for scheduling* (3rd ed.). Project Management Institute.
60. Raz, T., & Marshall, B. (1996). Effect of resource constraints on float calculations in project networks. *International Journal of Project Management*, 14(4), 241-248.
61. Sambasivan, M., & Soon, Y. W. (2007). Causes and effects of delays in Malaysian construction industry. *International Journal of Project Management*, 25(5), 517-526.
<https://doi.org/10.1016/j.ijproman.2006.11.007>
62. Schatteman, D., Herroelen, W., Van de Vonder, S., & Boone, A. (2008). Methodology for integrated risk management and proactive scheduling of construction projects. *Journal of Construction Engineering and Management*, 134(11), 885-893. [https://doi.org/10.1061/\(ASCE\)0733-9364\(2008\)134:11\(885\)](https://doi.org/10.1061/(ASCE)0733-9364(2008)134:11(885))
63. Son, J., & Skibniewski, M. J. (1999). Multiheuristic approach for resource leveling problem in construction engineering: Hybrid approach. *Journal of Construction Engineering and Management*, 125(1), 23-31. [https://doi.org/10.1061/\(ASCE\)0733-9364\(1999\)125:1\(23\)](https://doi.org/10.1061/(ASCE)0733-9364(1999)125:1(23))
64. Tranfield, D., Denyer, D., & Smart, P. (2003). Towards a methodology for developing evidence-informed management knowledge by means of systematic review. *British Journal of Management*, 14(3), 207-222.

65. Unamma, U. M.-L., Ashore-Onisemo, F., Iwuanyanwu, U., & Okwesa, I. J. (2018). Predictive forecasting for operational resource allocation: A comparative review. *Iconic Research and Engineering Journals*, 1(9), 493-508. <https://doi.org/10.64388/IREV119-1722628>
66. Van Slyke, R. M. (1963). Monte Carlo methods and the PERT problem. *Operations Research*, 11(5), 839-860. <https://doi.org/10.1287/opre.11.5.839>
67. Vandevoorde, S., & Vanhoucke, M. (2006). A comparison of different project duration forecasting methods using earned value metrics. *International Journal of Project Management*, 24(4), 289-302. <https://doi.org/10.1016/j.ijproman.2005.10.004>
68. Vanhoucke, M. (2010). Using activity sensitivity and network topology information to monitor project time performance. *Omega*, 38(5), 359-370.
69. Vanhoucke, M. (2013). *Project management with dynamic scheduling: Baseline scheduling, risk analysis and project control* (2nd ed.). Springer. <https://doi.org/10.1007/978-3-642-40438-2>
70. Vanhoucke, M., & Vandevoorde, S. (2007). A simulation and evaluation of earned value metrics to forecast the project duration. *Journal of the Operational Research Society*, 58(10), 1361-1374.
71. Ward, S., & Chapman, C. (2003). Transforming project risk management into project uncertainty management. *International Journal of Project Management*, 21(2), 97-105.
72. Wiest, J. D. (1964). Some properties of schedules for large projects with limited resources. *Operations Research*, 12(3), 395-418. <https://doi.org/10.1287/opre.12.3.395>
73. Williams, T. M. (1992). Criticality in stochastic networks. *Journal of the Operational Research Society*, 43(4), 353-357. <https://doi.org/10.1057/jors.1992.50>
74. Zidane, Y. J.-T., & Andersen, B. (2018). The top 10 universal delay factors in construction projects. *International Journal of Managing Projects in Business*, 11(3), 650-672. <https://doi.org/10.1108/IJMPB-05-2017-0052>
75. Zou, P. X. W., Zhang, G., & Wang, J. (2007). Understanding the key risks in construction projects in China. *International Journal of Project Management*, 25(6), 601-614. <https://doi.org/10.1016/j.ijproman.2007.03.001>