

Applications of Operations Research in Railway and Metro Systems:

A Critical Review

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<https://doi.org/10.55041/ijst.v2i10.022>

Cite this Article: Khandelwal, A., Neeraj, A., Phophaliya, A., Shekhar, A. & Ghiya, A. (2026). Applications of Operations Research in Railway and Metro Systems: A Critical Review. *International Journal of Science, Strategic Management and Technology*, 02(10), 1-9.
<https://doi.org/10.55041/ijst.v2i10.022>

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ABSTRACT

Railway scheduling covers more than one type of problem. For a construction project, the main concern may be how long the project will take. During railway operations, the problem can be quite different, such as deciding how train movements should be changed after a delay. This paper reviews five studies covering Nagpur Metro, Mumbai Metro Line 3, Beijing Subway Line 4, Jakarta Central Railway Station, and Indonesia's Double-Double Track Package A. The studies are compared in terms of their problem, objective, network structure, uncertainty, constraints, method, validation, and results. The comparison shows that CPM, PERT, crashing, Monte Carlo simulation, and real-time train rescheduling are being used for different purposes. Jakarta and Package A use probabilistic methods to estimate project completion. Mumbai reports Monte Carlo analysis, but does not provide enough information to reproduce the simulation. Beijing focuses on energy use and delay during train operations. The Nagpur study is more difficult to assess because only its abstract and publisher information could be accessed, and the publisher has duplicate records with different bibliographic details. For this reason, the review sticks to what can actually be supported by the available evidence. It also separates a model's forecast confidence from its actual demonstrated accuracy, which would need things such as back-testing and clearer information about the assumptions.

Keywords— Operations Research; CPM; PERT; Monte Carlo simulation; railway scheduling; train rescheduling

I. INTRODUCTION

Railway planning can involve very different time scales. Construction includes activities such as civil work, track work, station work and commissioning, which can continue for months or years. Train operations are different because a delay may have to be handled within minutes or hours while keeping the service safe. Both types of problems can be represented using networks and time constraints, which is where Operations Research (OR) becomes useful. OR provides ways to represent decisions, objectives and constraints in a structured form. The Critical Path Method (CPM) identifies the longest chain of precedence-linked activities and shows where schedule float exists. PERT and other risk-based methods can then be used when activity durations are uncertain [6], [8].

The five studies were chosen because they represent different uses of OR in railway construction and operations. Uparkar et al. discuss CPM, PERT and crashing for the Nagpur Metro project, although the full text was not accessible and the available publisher records contain

conflicting bibliographic information [1]. Lowe et al. examine time and cost risk for an underground Mumbai metro corridor using a reported Monte Carlo approach [2]. Huang et al. study real-time, energy-aware train rescheduling on Beijing Subway Line 4 [3]. Ichsan et al. combine CPM, PERT and Monte Carlo simulation for Jakarta Central Railway Station [4]. Riantini et al. use AHP to prioritise risks and then apply probabilistic PERT simulation to the Double-Double Track project [5].

The studies are compared mainly by asking three things: what decision the method is meant to support, how time and uncertainty are represented, and how well the reported result has been checked. This keeps project completion forecasts, time-cost decisions and real-time train rescheduling from being treated as the same problem. The methods are connected, but they do different jobs. For example, Monte Carlo simulation can show a range of possible outcomes without telling a manager which action to take. Similarly, a train-state representation used for operations is different from a CPM activity network.

II. LITERATURE REVIEW

Project scheduling starts with activities and the relationships between them. CPM calculates early and late dates from the activity durations and precedence relationships, which makes it possible to identify the critical path and available float. PERT is useful when activity durations are uncertain and normally uses optimistic, most-likely and pessimistic estimates. Crashing considers whether an activity can be completed faster by using additional resources, usually at an additional cost. In simple terms, CPM helps analyse the schedule, PERT deals with uncertain durations, and crashing deals with the time-cost trade-off [7]–[9]. Monte Carlo simulation can then take uncertain activity durations through the network repeatedly and produce a range of possible completion dates [6].

The five studies do not explain these steps to the same extent. Jakarta clearly combines a CPM baseline, three-point PERT estimates and 10,000 Monte Carlo iterations [4]. Package A uses AHP for risk prioritisation and 100,000 PERT-based Monte Carlo iterations, although the paper does not establish that a CPM algorithm itself was run [5]. The Monte Carlo method and a predecessor network are reported in Mumbai, but the distributions, the number of simulations, and the output distribution are not reported [2]. Nagpur mentions CPM/PERT and crashing but does not give any detail of the calculation or the results [1].

There is an operational literature, which contains the Beijing study. It identifies the primary delay and its propagation via train interaction,

and modifies future train movements in the presence of headway and safety constraints and platform capacity. The objective balances energy consumption with terminal delay, and a Hybrid Genetic Algorithm (HGA) is used to search for a feasible rescheduling solution [3]. This is an operational train-scheduling problem rather than a project-completion forecast. Its results should therefore not be directly compared with the number of construction days reported in the other studies.

III. METHODOLOGY

This paper is a focused review of the five studies supplied for the assignment. It does not try to cover every paper on railway scheduling. Publisher and repository information was checked for each source. The full primary articles were available for [2]–[5], while the Nagpur full text was subscription-gated, so its abstract and publisher information were used. The studies were then looked at using the same general points: application context, decision variables, objective, constraints, uncertainty, method or software, validation, reported outcome and limitations. Since the sources cover both construction planning and train operations, the comparison is based mainly on what each method is being used to decide rather than giving all five studies one overall numerical ranking.

A. CPM, PERT, and Crashing Model

The following equations explain standard project-scheduling concepts used for comparison; they are not presented as equations taken directly from any one of the reviewed articles. Let A be the activity set, E the set of precedence pairs, d_i the duration of activity i , s_i its start time, and T the project finish time. A simple deterministic network model can be written as:

$s_j \geq s_i + d_i$ for every $(i,j) \in E$; $T \geq s_i + d_i$ for each terminal activity i ; minimize T .

The forward pass calculates the earliest start and finish times. The backward pass calculates the latest dates that still allow the required project finish. Total float is obtained from the difference between the late and early dates. The longest precedence path gives the earliest project completion for the durations and network relationships being used. Activities on this path normally have the least float and, in a simple unconstrained network, usually have zero float [6], [8]. Costs and resources can also be added to a CPM model, but CPM itself is mainly a method for analysing the schedule.

This difference is important when the Nagpur study is considered. CPM can identify activities controlling a baseline schedule, but it does not by itself decide whether extra crews should be added, the sequence should be changed, or more money should be spent to finish earlier. Those decisions need additional variables and constraints, such as labour availability, allowable duration reductions and budget limits. PERT also introduces uncertainty into activity durations, but it does not choose the response to that risk. So, from the information that is available, mentioning CPM, PERT and crashing in the Nagpur paper is not enough to show that the authors solved one integrated mathematical optimisation model [1], [7]–[9].

PERT represents uncertain activity time using optimistic a_i , most-likely m_i , and pessimistic b_i estimates. The conventional expected duration and variance approximations are:

$$E[d_i] = (a_i + 4m_i + b_i) / 6; \quad \text{Var}(d_i) = ((b_i - a_i) / 6)^2.$$

PERT calculations are approximations. They do not mean that the final project completion time must follow an exact normal distribution. The result can change depending on the activity distributions used, dependencies between activities and the number of near-critical paths. In a Monte Carlo simulation, uncertain inputs are sampled repeatedly and the network is recalculated for each trial. This gives a distribution of possible completion times. If T is the simulated completion time and D is a target date, the proportion of simulations where $T \leq D$ estimates $P(T \leq D)$. This gives a forecast distribution, but it does not by itself tell the manager what action to take [6], [7].

In a simple linear crashing model, x_i denotes the duration reduction for activity i , with $0 \leq x_i \leq d_i^N - d_i^c$, where d_i^N and d_i^c are the normal and crash durations. The incremental cost slope is $(C_i^c - C_i^N) / (d_i^N - d_i^c)$. A model can minimize crash cost, given the precedence network and a desired completion time. If an activity is not critical the crashing does not reduce the duration of the project; if there are multiple critical paths, the multiple paths can be shortened at the same time [9].

B. Monte Carlo and Operational Rescheduling

The Monte Carlo analysis relies on stated probability distributions, number of runs, assumptions of dependence, risk events, a risk calendar, and a validation approach for forecast behaviour. Many iterations will help to get rid of the noise of the simulation, but will not correct for biased or unsupported inputs. It is particularly important to differentiate between the confidence level output of the report and forecast accuracy. The Jakarta and Package A articles show their number of iterations and confidence level, the Mumbai article doesn't provide equivalent implementation detail [2] [4] [5].

Huang et al. define a Train State Graph (TSG) to represent Train events & interactions for operational rescheduling. Their mixed-integer objective combines energy consumption with terminal travel delay, while the constraints cover train separation and braking safety, headway, movement-time limits, and platform capacity. A Primary Delay Identification Algorithm (PDIA) first identifies affected train sections before the HGA changes future movements [3]. The objective and constraints are operational and should not be treated as PERT or project-crashing models.

IV. RESULTS AND DISCUSSION

A. Nagpur Metro: CPM, PERT, and Crashing

The publisher abstract for the Nagpur Metro Rail Project describes an activity network and its precedence relationships. It identifies CPM and PERT as methods for scheduling and completion-time analysis and describes crashing as adding labour or other resources to reduce the project duration at a higher cost [1]. This is enough to classify the study as a network scheduling problem involving a time–cost trade-off. The accessible material, however, does not provide the activity list, durations, three-point estimates, critical path, cost slopes, software, numerical results or validation. The detailed technical model therefore cannot be reconstructed from the material that was available.

There is also a bibliographic problem with the Nagpur source. The publisher has two records with the same title, authors and abstract, but different volume, issue and page details: volume 29(7), pages 3507–3515, and volume 29(08), pages 4055–4064. There was no explanation on the site about whether the second entry is correction, reissue or duplicate; none of the linked pdfs was accessible. This review considers them as one study and not counts secondary claims as filling the gap. The Nagpur source is thus evidence not of any specific PERT formula but of the authors' CPM/PERT/crashing [1].

B. Underground Mumbai Metro: Network Risk Estimates

Lowe, Nagarajan and Narwade cover the underground Mumbai Metro Line 3 with a length of 33.5km, 26 stations and 2 depots. The article presents 18 activities (A–R) in a predecessor network and seven paths. Primavera Project P6 is called 'activity programming' and a Monte Carlo Simulation Method is reported in the paper in addition to the CPM/PERT terminology [2]. The intent of its practical application is to estimate exposure to time and cost of activities, and to identify critical or near-critical paths, not to optimize a series of activity decisions.

According to the paper, the critical path has been delayed by 1,875 days comes at INR 122.28 crore, a delay from A-C-E-D-G-I-R. According to its summary table, base rate/cost INR 28.3 billion, risk rate/cost INR 4.9 billion, anticipated rate/cost INR 33.2 billion, base time (1 year) 1,538.75 days, risk time (1 year) 336.25 days, and anticipated time (1 year) 1,875 days. But there's an earlier travel time of 3,700 days for INR 1,220 million in the network table. There are also differences in other activity inputs and percentage calculations across sections [2].

The help that one works risk calculation can help clarify the reported structure of the article. The story provides Activity A with a risk factor of 0.348, base rate of INR 240 million, corrective rate of INR 60 million, base time of 1,538.75 days, and corrective time of 1,130 days. The article then multiplies the risk factor by corrective rate/time to come up with INR 20.88 million and 336.25 days, and then adds risk time to the base time, which equates to 1,875 days. It also mentions tolerance of 25% of rate overrun and 30% of time overrun [2]. This is a scenario weighted calculation, not a full specified probability distribution or a cost minimizing decision model.

The article presents the WBS, precedence network, activity-level risk arithmetic, and the path calculations, but not the probability distributions, the number of iterations, the random seed and any

separate simulation software to enable readers to reproduce Monte Carlo results. It does not include any external back testing of real project completion or cost. The authors' 5% successful-completion figure is a model figure, not a stand-alone probability. The interpretation of the forecast is significantly hampered by reporting and internal consistency problems [2].

The difference is not simply a bibliographic one. The previous 3,700-day statement and later, one of 1,875 days, suggest materially different completion projections. The article also alternates between narrative and tabular presentation of activity-A entries, and gives rates in several different units. Since the Monte Carlo inputs and trial settings are irretrievable, this review uses published figures as claims, and identifies internal conflicts without making a selection as a corrected result. A proper replication would require the underlying schedule, risk register, and simulation specification from the authors [2].

C. Beijing Line 4: Real-Time Energy-Saving Train Rescheduling

Huang, Li and Schonfeld examine peak-period rescheduling on Beijing Subway Line 4, which has 35 stations and 36 trains with 100-second headways. Their method first separates primary delays from delays that result from train interactions. PDIA, the Primary Delay Identification Algorithm, is then used to identify affected trains and sections. The second stage uses a constrained mixed-integer model together with a Hybrid Genetic Algorithm (HGA). The decision variables concern the affected train station times or equivalent affected-section trip times, while the objective balances energy cost against terminal delay [3].

The model includes minimum separation and braking-safety constraints, headway requirements, dwell and section times, platform capacity and timetable deviations. The authors assume FIFO operation without overtaking, a straight and level line, steady passenger flow, no stop-skipping, unaffected rolling-stock scheduling and no severe-disruption scenario. PDIA reportedly identified the primary delays with 100% accuracy in three constructed cases. In the HGA simulations, the reported objective cost was reduced by 13.62%–15.42% compared with the original schedules. HGA also performed better than the generic GA comparator and completed within eight minutes in the reported experiments [3].

The TSG represents train events at both macro and micro levels: arrivals and departures at stations, and acceleration, cruising, or deceleration states between stations. Arcs connect successive states of the same train, while interaction links represent the effect of a preceding train on the following train's safe movement. The safety distance combines a minimum margin with a braking-distance term based on speed and braking capability. By restricting optimization to future affected sections, PDIA reduces the number of decision variables compared with changing all remaining trips. It is reported that there are 44 HGA decision variables in the paper, and 278 generic-GA ones in the paper [3].

The study is also of an operational nature: identify energy and delay trade-offs and detect delay propagation prior to timetable change. It is not a PERT, a crashing or a construction CPM baseline. Its evidence is stronger than a single non benchmarked heuristic run, due to its comparison, weights, and supporting evidence. However, the cases presented are simulations on a single line, and the assumptions made by the authors restrict transfer to severe incidents or to other track geometry or to systems with other passenger or rolling-stock constraints [3].

Validation includes multiple checks instead of a single headline percentage. PDIA is tested against known primary delays in three scenarios, and its computation time is compared with an original critical-path search and a repeated-simulation search. HGA is compared with a generic GA, and convergence is also examined. The authors repeat a case with independent runs and change the energy/delay weights and unit costs. HGA gives reported objective-cost reductions of about 13.62%–15.42% in the tested cases, while the generic GA gives smaller reductions [3]. These are still simulation-based comparisons, though, and the study does not report a field trial or an optimality certificate.

D. Jakarta Central Station: CPM, PERT, and Monte Carlo Forecasting

Ichsan, Isvara, and Karim analyze Phase II construction of Jakarta Central Railway Station. The planned contract ran from 11 October 2019 to 30 September 2021 (674 days); archived progress at the planned finish was 42.08%, and the paper reports actual completion on

31 January 2024. CPM in MS Project V2016 identifies nine critical activities. Five experienced respondents validated 22 of 51 delay indicators, and six dominant risks were linked to critical work, including live-train switch-over sequencing, delayed work permits, phase interfaces, work on active tracks, owner decisions, and multi-party permitting [4].

The authors provide optimistic, most-likely, and pessimistic risk-delay estimates, use PERT, and run 10,000 iterations in @RISK V8.5.1. Under inherent risk, the article reports 1,555.66 days from PERT and simulated completion totals of 1,575.70, 1,584.78, and 1,592.33 days at 80%, 90%, and 95% levels. Under post-mitigation risk, it reports 1,319.82 PERT days and 1,342.26, 1,354.10, and 1,363.02 simulated days at the same levels [4].

The article also transfers the activity-level values back into MS Project to obtain schedule dates. The pre-mitigation forecasts are much longer than the 674-day contract schedule, while the post-mitigation forecasts are shorter and differ according to the confidence level. This can help when choosing a contingency date based on how much risk a decision maker is willing to accept. The 80%, 90% and 95% values are still model quantiles, though. They do not show that forecasts at those levels have actually achieved the same coverage in practice. A back-test using the eventual completion date of 31 January 2024 would be needed to examine predictive calibration [4].

For each selected critical activity, the PERT inputs represent pessimistic, most-likely, and optimistic risk-delay values. The most consequential live-operation risk, train operating-pattern and switch-over sequencing (R10), receives the largest inputs; activity A is assigned 720/700/680 days before mitigation and 550/500/470 days afterward in the paper's P/ML/O table. The scenario design therefore links the identified mitigation measures to changes in the modeled delay inputs and then propagates those changes through the schedule [4]. The interpretation still depends on expert judgment and on the article's unreported dependence structure among risks.

Among the five studies, Jakarta is the clearest construction example where a CPM baseline, three-point PERT inputs and simulation are used together. The paper gives the software, number of iterations, risk-to-activity mapping and scenarios, so the method is relatively easy to follow. The validation is still mainly based on expert and instrument checks rather than an independent forecast back-test. Therefore, the 95% result should not be read as 95% proven accuracy. The paper also does not explain risk correlation, sensitivity analysis or detailed resource and calendar modelling [4].

E. Double-Double Track Package A: Probabilistic PERT Forecasting

Riantini et al. study an Indonesian double-double-track development project financed through State Sharia Securities. The analysis combines AHP risk prioritization, expert estimates, PERT distributions, and 100,000 Monte Carlo iterations using @RISK 8.2. The risk survey involved 26 practitioners and three domain experts. The dominant risks were stakeholder coordination and changes in scope or design review. The authors link these risks to selected critical-path activities and compare completion forecasts at 90%, 95%, and 99% confidence levels [5].

The study divides risk screening into track works, railway bridge structure, station buildings, and operation facilities. Pairwise comparisons use the AHP 1–9 scale, while probability and impact are scored on five-point scales. Reported risk-priority values identify stakeholder coordination as dominant in track work (0.525), bridge structure (0.606), and operation facilities (0.597), while scope change/design review is dominant for station buildings (0.529) [5]. The study then associates these risks with critical-path activities and obtains three-point duration estimates from practitioners. This makes the risk-identification process visible, although the complete activity network is not reported in a form that would allow independent reconstruction.

At the selected 95% level, the post-optimisation forecast is 30 March 2024, compared with the secondary schedule date of 29 December 2023. The difference is 93 days. The paper gives a clear risk-prioritisation procedure and reports the simulation scale and software. The term "optimisation" should still be treated carefully here. The study does not set up a conventional cost, resource or crashing optimisation problem, and discussing critical-path activities does not by itself verify that a CPM algorithm was actually run [5].

The AHP consistency ratio reported by the study is 5.31%, and 100,000 @RISK iterations are used for the 90%, 95% and 99% outputs. The authors select the 95% level as the final forecast, but selecting that level does not establish that the forecast has 95% empirical coverage. The model assumes independent stochastic factors, even though risks such as stakeholder coordination and design changes may be related in practice. Correlated-risk scenarios, sensitivity analysis and comparison with the actual completion date would make the evidence stronger [5].

Validation concerns questionnaire review, expert judgment, and AHP consistency (reported CR 5.31%) rather than comparison with an independently observed forecast error. The paper assumes independent duration risks but does not explain how correlation or critical-path recomputation is handled during simulation. It doesn't do demonstrated coverage — its 95% result is only a model quantile. This setting of the single project and subjective durations are further to restrict generalization [5].

The five cases vary in terms of decision role and the level of evidence:

Nagpur [1] — There is no technical output verification, and only abstract-level evidence is available, such as CPM/PERT/crashing.

Mumbai is a network/path risk estimate reported, but sampling details are missing and there are some conflicts of numbers in the claims. Beijing [3] — online energy-delay rescheduling using PDIA and HGA/MIP; simulated comparisons are reported, but no live trial.

Jakarta [4] — a CPM baseline with three-point PERT and 10,000-run Monte Carlo; expert validation is not independent forecast testing.

Double-Double Track [5] — AHP risk ranking with PERT/100,000-run Monte Carlo; CPM/crashing and out-of-sample validation are not verified.

F. Comparative Analysis and Critical Reflection

The five studies share network representations but differ in what a path represents. In the construction papers, paths connect project activities and support forecasts of total completion time. In Beijing, a path through the train-state graph represents interactions and delay propagation during service. Only the Beijing study optimizes operational movements against an energy-delay objective. Consequently, neither its 13.62%–15.42% objective-cost reductions nor the construction studies' days, risk percentages, or confidence levels provide a common performance ranking [2]–[5]. Nagpur has no accessible numerical result to compare [1].

The studies are also not equally easy to reproduce. Jakarta and Package A give PERT inputs or simulation settings and identify the software used. Beijing provides case parameters, algorithm comparisons and sensitivity tests. Mumbai gives the activities and paths, but not enough stochastic information to recreate the Monte Carlo procedure, and its numerical inconsistencies make the results harder to interpret. Nagpur cannot be checked beyond its abstract because the full text was inaccessible. In the construction studies, expert estimates and scenario outputs therefore need to be kept separate from independent empirical validation.

One useful way to look across the studies is to separate model specification from validation. For specification, the question is whether another reader could rebuild the network, inputs, objective, constraints and software. Validation is concerned with whether the results of the model have been compared to an independent source of truth or if they have been compared only against other experts and/or other models. Beijing offers more detailed experiments with the algorithms and data sets, but no live implementation. No independent forecast-coverage tests are provided by Jakarta and Package A. Mumbai provides case tables, but the Monte Carlo settings are not enough and there are numerical conflicts. The abstract is all that can be judged for Nagpur. This is a comparison of reporting evidence, rather than a comparison of the technical competence of the authors.

The lesson that can be learnt from this is to make sure that the method suits the decision. CPM is suitable for a precedence baseline (deterministic) and for criticality analysis. PERT adds uncertainty in durations and Monte Carlo can propagate specified distributions and dependence through a network. Crashing is prescriptive only if duration reductions for eligibility and costs are modeled. For real-time rescheduling, train movement, safety, headway, passenger and energy constraints are needed. Provision of a forecast completion date does not define the minimum cost mitigation plan or an operational recovery timeline. Future studies should publish complete activity or train networks, data provenance, units and calendars, distributions and

dependence assumptions, risk mappings, iteration counts and seeds, software versions, and validation data. Historical back-test results of construction forecasts should be covered, error metrics should be included and results from the Monte Carlo should be sensitivity tested for common cause risks and near critical paths. For mitigation, resource limits and explicit time-cost decisions are added. Tested schedule recovery should be considered on more lines, disruption types, passenger loads and field/digital-twin data for operations. A possible integrated research program might tie project-level risk forecasts to the rolling train rescheduling and still maintain the separation between forecasting and optimization.

V. CONCLUSION

This review concludes that five railway studies are using OR at various decision levels. According to its publisher, Nagpur is a CPM/PERT/crashing application, but there is no technical verification due to the duplicate metadata and inaccessibility of the full text. Mumbai provides network-based time and cost risk estimates via Monte Carlo, but incomplete disclosure of the simulation and conflicting numerical conclusions hampers reproducibility. The outputs of the confidence measures do not correspond to forecasts of accuracy, and confidence is not independently validated in Jakarta and Package A. Beijing tackles a unique operating challenge, and provides energy-delay gains for simulated train-rescheduling scenarios.

The CPM, PERT, crashing and Monte Carlo forecasting are complementary rather than replacement tools for real-time rescheduling. The following is a list of requirements for a credible OR review: Model decision variables are separated from model forecasts; Uncertainty quantiles are differentiated from observed accuracy; Assumptions and validation of the model are reported along with the results. Future railway scheduling studies would be enhanced by increasing the transparency of the inputs, back-testing, dependency analysis and reproducible case comparison.

ACKNOWLEDGMENT

The authors of the reviewed studies are acknowledged for making their work available. No funding information was supplied for this review.

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