# RISK.2196

# Removing the Early-Dates Bias in CPM Risk Analysis

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**Abstract—**The Critical Path Method (CPM) schedules activities to start on early dates, which results in an unrealistic completion distribution in CPM risk analysis. CPM risk analysis tools, thus, cannot model what commonly occurs when a project unfolds and activities start on dates later than early dates due to floating or pacing decisions based on schedule progress. Graphical Path Method (GPM®) risk analysis allows activities in each realization to float as a function of random sampling and decision rules, accurately modeling the real world where activities are delayed to take advantage of total float. This paper demonstrates how the early bias in CPM risk analysis leads to optimistic completion distributions, and how GPM risk analysis corrects for the early bias by allowing floating and pacing scenarios. A novel approach is also introduced for developing a bounding completion distribution envelope for selecting realistic probabilistic completion dates and for monitoring safe-float use as the project progresses.



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## Introduction

Project schedules are commonly subject to uncertainties in design, permitting, production rates, weather, site conditions, etc. that lead to risk in cost and duration. Program Evaluation and Review Technique (PERT) was developed in 1957 to analyze the network with consideration to uncertain durations using a beta distribution. MacCrimmon & Ryavec [4] and Van Slyke [9] identified several deficiencies to modeling uncertainty in project networks in the PERT approach, such as:

- merge bias;
- inability to consider resource allocations;
- inability to consider correlations between activity durations; and
- most importantly, the assumption that uncertainty in all durations is beta distributed with a standard deviation equal to 1/6 of the range.

MacCrimmon & Ryavec [4] also estimated errors introduced by each PERT assumption in calculating the project mean duration and standard deviation, which can be as high as 30% and 15%, respectively. With the aim of improving the PERT approach and its assumptions, Van Slyke [8] introduced a Monte Carlo simulation approach to evaluating uncertainty in network schedules. Monte Carlo simulation utilizes a longest-path algorithm (e.g., critical path method/CPM) to create multiple iterations of the network, which are then analyzed and used to generate a probability distribution for the overall project duration. This simulation-based approach simplified the process by allowing use of any probability distribution and did not rely on any simplifying mathematical assumptions as with PERT. Over the past few decades, this approach to evaluating uncertainty in the project schedule has gained acceptance owing to the relative ease in executing the simulation and analyzing the results, coupled with the immense growth in computational capabilities. Since the introduction of this approach over the past 50 years, CPM scheduling algorithms have largely remained as they were when introduced and the impact of CPM assumptions on schedule risk analysis has not been studied.

An important step in any simulation study is to validate the model and its assumptions to confirm that they accurately represent the actual system under review. Schedules are commonly modeled as CPM networks, and the uncertainty is described using probability distributions for activity durations. In this paper, the authors discuss how the CPM early-dates assumption, which is inherent in CPM-based simulation, introduces an optimistic bias in the simulation results and present an approach for modeling the schedule using Graphical Path Method (GPM®) algorithms [6]. Further, a case study illustrates the bias introduced by the early-dates assumption in CPM, which results in overestimating the likelihood of a project completing by the required completion date. The case study also demonstrates the inability of CPM-based simulation methods to model real-world decision scenarios—such as floating and pacing—and how GPM-based simulation techniques can be used to correctly model such schedule scenarios. A summary of the results from the case study clearly exposes the early-dates bias in CPM-based schedule simulation methods and the effectiveness of GPM risk analysis to remove early-dates bias from the simulation results.


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Also described in this paper is a novel methodology to develop a bounding completion distribution envelope for selecting realistic probabilistic completion dates and for monitoring safe-float use as the project progresses.

## Graphical Path Method (GPM)

GPM embodies alternate scheduling algorithms that transform conventional CPM planning and scheduling by making it an engaging, interactive, real-time process anchored in a computerized, graphical, object-based project networking method [5]. The method introduces the concept of planned dates that are defined by the user developing the schedule by placing an activity or another schedule object between the early and late dates. Unlike CPM algorithms that calculate early and late dates, GPM algorithms use planned dates as input to evaluate drift and float for each activity. For a task in GPM, float is defined as the duration by which its end could be delayed without affecting the project end date, similar to the definition of total float in CPM. Hence, float can also be defined as the duration between the planned and late finish date for the task. Drift is unique to GPM and is defined as the extent by which the start of an activity can be moved earlier without affecting the project start date. As is the case with float, drift can also be calculated as the duration between the early and planned start of a task. Since CPM always schedules tasks to start on early dates, drift in CPM schedules is always zero. This leads to an important result, wherein the sum of drift and float is equal to the total float for any task. As GPM algorithms do not require the use of constraints to schedule a later start for the activity, planned dates do not artificially alter the total float of an activity. This makes the approach invaluable for simulations wherein the use of constraints can significantly impact the results and, hence, is considered bad practice [2]. GPM-based simulation methods thereby provide an ideal approach to model floating and pacing scenarios as described later in the paper.

## Early-Dates Bias in CPM

The CPM algorithm calculates the network in two steps: forward pass and backward pass. The forward pass begins at the project start event and calculates early start and early finish dates for each activity. If only finish-to-start logic is used, the early start date of any activity is calculated as the latest early finish date of its predecessors, thereby placing the activity on the earliest day it can begin. During the backward pass, late dates and total floats are calculated based on the project completion date, and the critical path is revealed as the path of activities with zero or least total float.

CPM- and Monte-Carlo-based risk simulations represent a significant improvement over the PERT methodology. The results of the simulation overcome the merge bias in the PERT early-dates solution by using actual, randomly sampled activity durations, and by determining the longest path to every activity that results from sampled durations and the early-dates limitation. However, the early-dates limitation in the CPM-based approach does not account for the merge bias associated with late starts, resulting in optimistic probabilistic estimates of the


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project completion date. On real-world projects, activities off the critical path are often "floated" to start later as a strategic decision to control progress or to "pace" due to delays in other paths of the network. This type of decision introduces floating or pacing risk, which, coupled with the uncertainty in the duration of the activity itself, may delay a noncritical activity to the point that it becomes critical. A floating and/or pacing decision, in effect, can cause a critical path delay, thereby affecting the project completion date.

Gong & Rowings Jr. [3] demonstrate how the underlying reason for this floating or pacing risk eventually stems from the concept of merge bias. As more and more competing paths merge at an event, the expected date of the merge event is much later than the PERT expected date. Merging activities with high total float (and comparatively low duration uncertainty) do not compete with other longer merging paths and do not therefore affect the expected date of the merge event. However, when these activities are floated or paced by consuming available float, the delay in start puts them closer to the merge event, alters the merge risk, and, coupled with the duration uncertainty, eventually impacts the event's expected date. This ultimately reveals a significant under-estimation of the project duration or of the overall completion date by PERT or CPM-based risk simulation methods. Their paper also describes an approach to mathematically develop the safe-float-use range for each merging activity utilizing individual probability distributions for each activity. The safe-float use by any activity is then defined as the amount of maximum float that can be used without delaying the expected date of the merge event. However, the method proceeds iteratively for each activity and can quickly become complicated when many paths merge together as predecessors to an activity.

**Base-Case Scenario**

The case study involves a design-build contract for the rebuild of a food processing facility. For confidentiality, activity durations and logic ties have been slightly altered. Figure 5 shows the level 1 base-case deterministic schedule from *Design NTP* to *Ready for Commissioning* using NetPoint®, a GPM/CPM scheduling tool. The base-case schedule shows all activities on their early start dates as scheduled using the CPM scheduling algorithm. The required completion date for the project is 10/06/2012. As represented by the deterministic scenario, the total duration of the project is 328 days with 41 days of schedule margin between the planned completion date (08/26/2012) and the required completion date. Activities on the deterministic critical path with zero total float are shown in red.

A stochastic model of the schedule was built by ranging activity durations using three-point estimates detailed in  and assuming triangular distributions. For simplicity, only duration uncertainty was modelled; risk events (or GPM prime risks [7]) were not included in the analysis. However, the underlying methods and analysis are equally applicable when risks are modeled to impact activity durations in the schedule as described in RP 57R-09 [2]. The base scenario was then simulated in NetRisk™, a GPM/CPM risk tool, using CPM algorithms to develop a cumulative distribution curve for the schedule completion date as shown in Figure . The results indicate that the earliest possible completion date for the project is 08/28/2012,


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implying a 0% chance of completing the project by the deterministic end date of 08/26/2012. Figure 1 also indicates there is an 80% chance of completing the project by 10/01/2012 (i.e., 35 days after the planned completion), but only five days before the required completion date.
In the deterministic schedule, the highest total-float path (with two or more activities) is through activities related to elevator fabrication and installation. These activities have 69 days of total float (28 days of total float + 41 days of margin), which is 18.7% of the project duration up to the required completion date. The second highest-float path is through the Electrical Equipment fabrication and installation work and has 61 days of total float, which is 16.5% of the project duration up to the required completion date. Based on the results of the simulation, Figure shows all of the activities at $50^{th}$ percentile durations; the criticality indices of the activities are displayed below them. As per RP 10S-90 [1], criticality index describes how often an activity was on the critical path during the simulation, which is expressed as a number between 0 and 1. For this scenario, it can be seen that criticality indices for activities on the elevator and electrical equipment paths are 0% and 25.3% respectively.

**Floating and Pacing Scenarios**

Owing to the high total float of the elevator and electrical activities, it is possible during execution of the project to delay the start of these activities to some extent from their early start dates. However, a decision to delay an activity can be completely random or may be based on how progress on other activities is affecting the available total float for that activity. Current CPM-based simulation methods in each iteration place activities on early dates, thus, not providing a way to model such scenarios or decision making in the simulation. This imposes a significant limitation and introduces a deviation in the behavior of the model as compared to the actual system. GPM-based simulation algorithms differ from CPM simulation in two fundamental respects. First, each iteration unfolds, from the project start to completion, as a simulated update of the base case in that activities have dates and float values that are revised to reflect sampling. Second, activities may be scheduled on planned dates, either because planned dates were present in the base case or because activities are allowed to start on randomly generated planned dates due to floating or pacing decisions. This allows the user to anticipate such conditions and quantitatively plan for their effect on the overall schedule in a more realistic manner.

For the case study, floating scenarios were modeled first; pacing was added in a subsequent analysis. In GPM risk, floating takes place based on a random decision to float or not to float using a user-defined threshold probability for each iteration. To model this scenario and for simplicity, the *Electrical Equipment Shops*, *Electrical Equipment Installation*, and *Elevator Fabrication & Delivery* activities were allowed to float 80% of the time by consuming up to 80% of their *then-available* float during an iteration. Although two activities on the *Electrical Equipment* path are floated in this scenario, for every floating-eligible activity, the *then-available* float during an iteration is used to determine the extent by which an activity is floated. Hence, if both *Electrical Equipment* activities are floated in the same iteration, the floating decision for the *Electrical Equipment Installation* activity will take into consideration the


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float *then-available* after *Electrical Equipment Shops* has already floated. Even though in this case the floating scenario consumes only 80% of the *then-available* float, a decision to float predates actual performance of the activity (i.e., how long it might actually take). Therefore, in that iteration (as in a real-world project), the floated activity can become critical if the sampled duration exceeds the base-case duration by more than 20% of the *then-available* float after floating. In such a scenario, the decision to float the activity can lead to a delay in the project completion date.

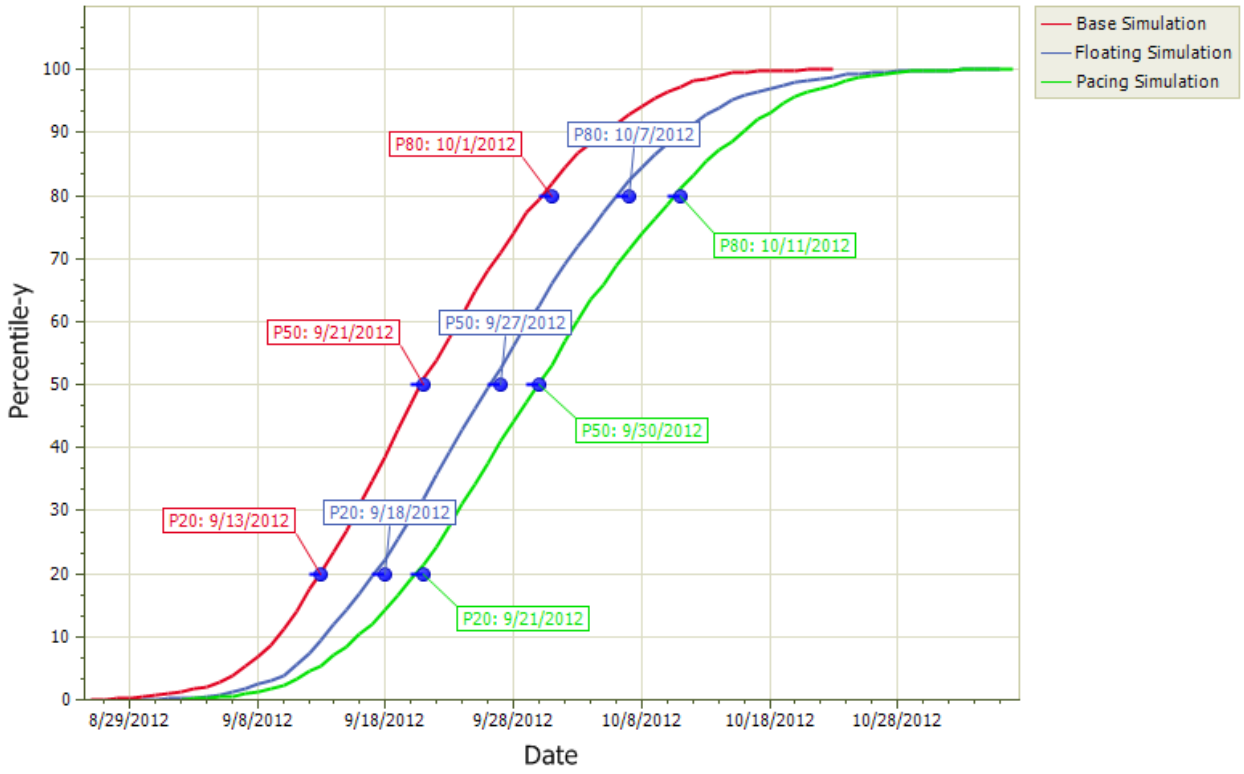



**Figure 1 – Project Completion Date Curves for Base, Floating, and Pacing Scenarios**[1]

The cumulative project completion curve for the floating scenario is shown in Figure , which illustrates that the 80% confidence date shifts out to 10/7/2012 or six days later than the base scenario (CPM simulation) model, and one day after the required completion date. As expected, the criticality index for activities on the electrical equipment fabrication and installation path has increased to 54%, yet activities on the elevator path still remain off the significant critical path. Floating and pacing activities off the critical path push them to complete closer to the merge events, thereby significantly increasing the merge risk. The CPM risk model predicted sufficient schedule margin based on an 80% completion likelihood by the required completion date of 10/06/2012. However, the GPM risk model reveals that margin in the deterministic schedule is one day short of maintaining an 80% project completion likelihood affected by floating decision-making in the model.

[1] Figures 1, 2, 5 and 6 are screenshots from PMA Technologies, NetRisk™ v2.0 and NetPoint® v5.1


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Pacing is also based on a random decision to pace or not to pace. Pacing differs from floating, however, in that the start of an activity is deferred/paced only if its *then-available* float exceeds the activity's float in the base-case scenario by a user-defined threshold. In a real-world scenario, an activity becomes eligible for pacing when delay on an unrelated path is controlling progress to the point that the activity is gaining float. Under such conditions, it does not make sense to start the activity only to then "hurry up and wait." Such a pacing scenario can be represented in GPM risk models by defining a threshold for the *then-available* float for an activity with respect to the deterministic float and a probability distribution for the days to pace the activity.

For the case study, the activity "*Building Permit*" is off the deterministic critical path and has 17 days of total float in the base case. The pacing scenario is modeled to attempt to pace this activity 80% of the time by 80% of its *then-available* float. In the iteration provided, its *then-available* float is more than 50% of its deterministic float. The cumulative project completion curve (Figure ) for the pacing scenario predicts that the 80$^{th}$ percentile completion date gets pushed back to 10/11/2012, which is five days past the required completion date. This date is also 10 days later than the 80$^{th}$ percentile completion date that the CPM-based simulation predicted. The pacing scenario on the "*Building Permit*" activity increases its criticality index from 38% to 52% in the floating scenario. Consequently, the criticality index of the electrical equipment path falls to 43%.

The maximum delay possible to the project completion date caused by randomly floating activities in the schedule is theoretically unbounded. However, under the assumption that activities can only be floated by the *then-available* float, the maximum project completion delay can be calculated. For this, an upper-bound floating scenario can be defined by floating all activities 100% of the time by an extent equal to the *then-available* float for each activity. The base-simulation/CPM early scenario and the late dates/100% floating scenario together form a bounding envelope for the project completion probability curve. This envelope represents all possible minimum and maximum probability curves for various floating/pacing scenarios for the schedule. Figure shows the floating envelope developed for the schedule: P80 completion dates for the base-case and bounding floating scenario are 10/01/2012 and 10/16/2012, respectively. In other words, conventional CPM-based schedule risk analysis leads to optimistic estimates of a project completion date distribution due to its early-dates bias. As determined in the scenario above, the CPM-based simulation predicted an 80% chance of completing the project by 10/01/2012. Depending on the likelihood of floating or pacing in the actual project, however, that date may have had a much lower likelihood of meeting the required completion date.

**Safe-Float-Use Envelope**

The case study clearly demonstrates how simulation models developed using GPM algorithms provide a significant improvement over a CPM-based approach. GPM models allow the user to realistically represent floating and pacing scenarios, which, in turn, reveals an unbiased estimate and distribution of the project completion date. Further established by the study,


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floating and pacing decisions off the critical path can still impact the project completion date as network activity duration uncertainty needs to be addressed in the iteration subsequent to a floating or pacing decision. This leads to a problem: how can safe-float use for a network be determined such that an activity off the critical path can be safely delayed without any significant impact on the likelihood of meeting the project completion date?

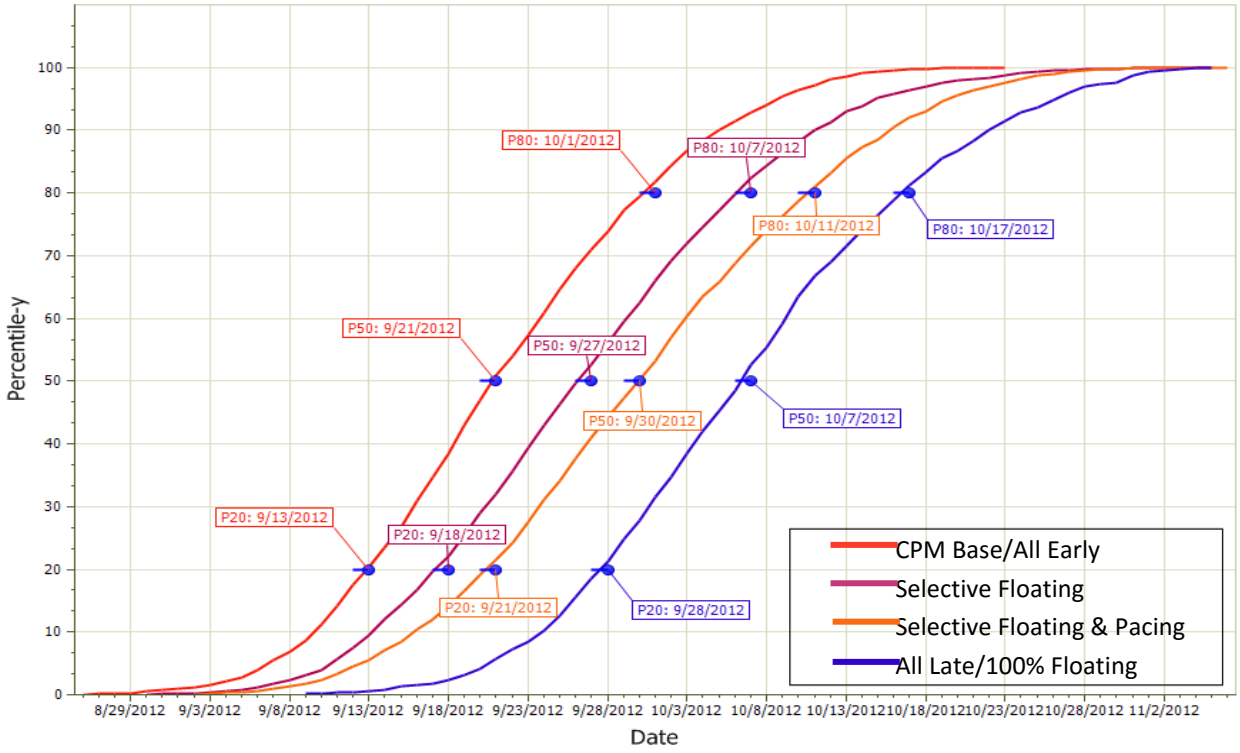



**Figure 2 – Floating Envelope**

This section describes a simple method for evaluating the latest start date for any activity that preserves the likelihood of on-time completion for a project schedule with activities of uncertain duration. The method involves careful analysis of the simulation results from the base-case scenario, which can be used to develop an envelope of safe-floating start dates for all activities in the schedule. The safe-float envelope for any activity is described as the duration between the earliest start date and the latest start date that does not impact the likelihood of the project completing beyond the required completion date.

Figure  shows the probability distribution for the start date of activity *Electrical Equipment Installation* from the base-scenario simulation. The simulation was carried out for 3,000 iterations; the observed earliest and latest start dates of the activity during the simulation were 05/10/2012 and 07/15/2012, respectively. Each iteration was analyzed to identify where the *Electrical Equipment Installation* activity was critical and the project completion was delayed past the required completion date of 10/06/2012. Figure  overlaps the probabilities of completing the project with or without delay with the start date probability distribution for the activity *Electrical Equipment Installation*. From the graph it can be inferred that there is 0%


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probability of a delay to project completion when the activity *Electrical Equipment Installation* starts on or before 06/30/2012. Thus, it is safe to float the activity as long as the activity starts on or before this date. It must be noted that the delay in the graph represents only the iterations where the activity was on the critical path and project completion was past the required completion date. Therefore, starting the activity before the safe-float-use date does not ensure on-time completion of the project since other paths in the network can still delay the end of the project.

Although the above discussion demonstrates the calculation of safe-float use for floating scenarios, the results hold true, however, for any cumulative impacts (or delays) leading up to the start of an activity. Even when multiple activities on the same path are floated, the results of the above analysis are equally applicable as long as the activities, their duration and uncertainty, and logic relationships in the schedule remain unchanged. The results must be revised when/if any activity is added or removed from the schedule or if relationships are modified. Although the above demonstration calculates the safe-float use for an activity off the deterministic critical path, the process can similarly be applied to any other activity in the network on or off of the critical path.

Owing to the simplicity in the structure of the schedule and to the underlying uncertainty, the results of the above analysis can be easily validated mathematically using simple concepts of probability. Starting from activity *Electrical Equipment Installation*, there is only one path (via *MEP Process Equipment* & *Install/Connect Process Equipment*) that leads to the project completion benchmark, *Ready for Commissioning*. The sum of the pessimistic durations for activities on this path is 105 days. Using this duration and the required completion date of 10/06/2012, the latest start date for activity *Electrical Equipment Installation* to avoid delay will be 06/24/2012. This is six days earlier than the safe-float-use date of 06/30/2012 (i.e., 99 days before the required completion date) calculated above. From the duration distributions defined for these activities, the probability that the sum of their sampled durations is greater than 99 days is only about $4.5 \times 10^{-3}$. The overall probability that the sampled duration is greater than 99 days and greater than the length of other paths, which would make these activities critical, is much lower. This makes its impact nonexistent in the simulation results, thereby justifying the safe-float-use date of 06/30/2012.


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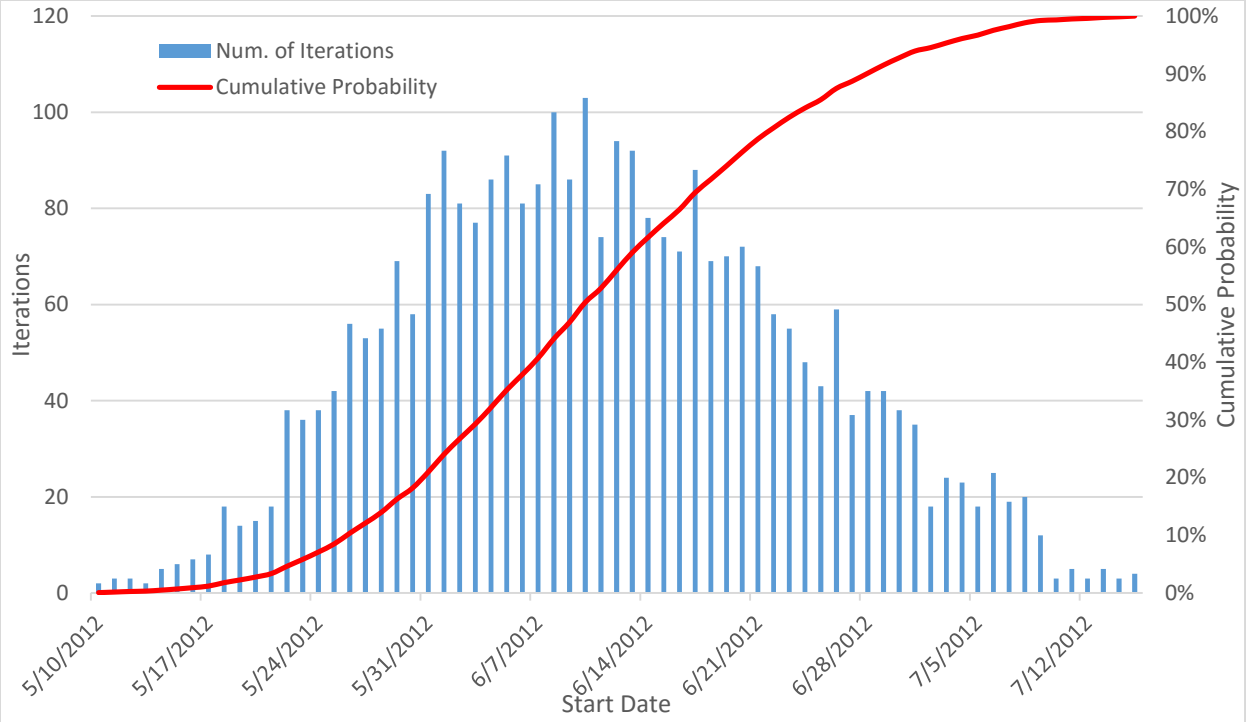



**Figure 3 – Start Date Distribution for Activity "Electrical Equipment Installation"**

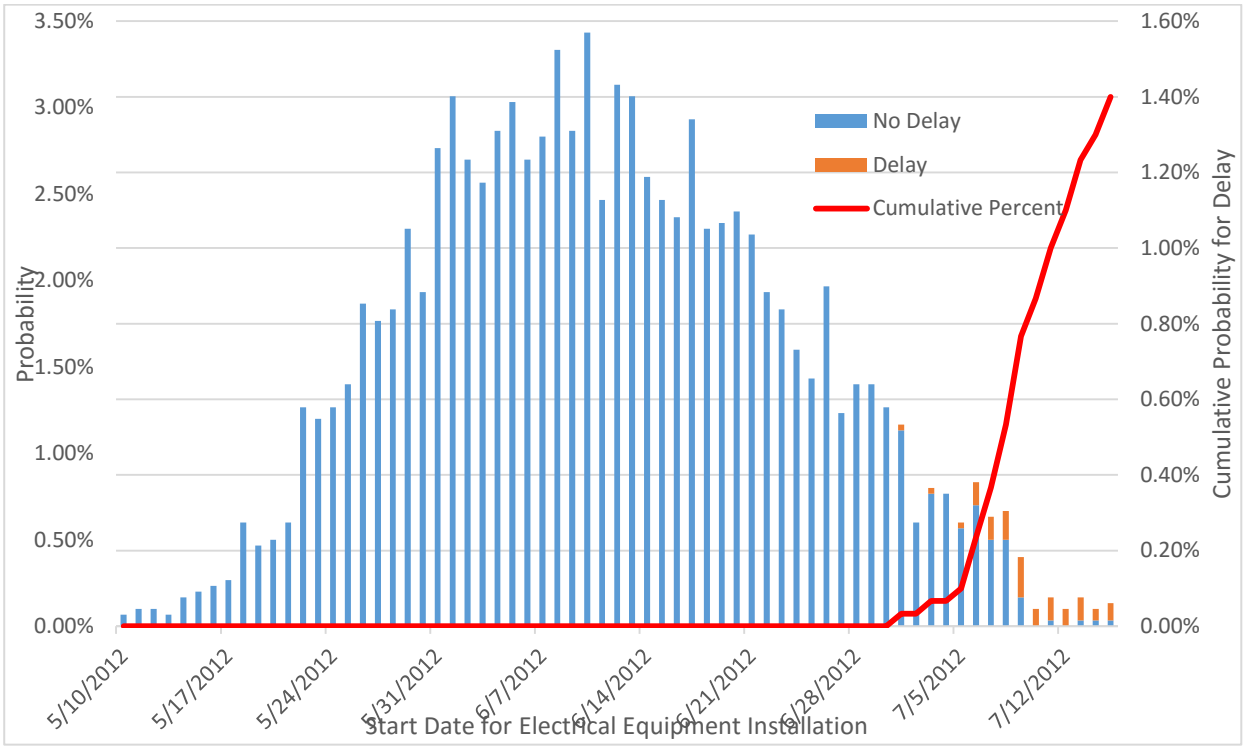



**Figure 4 – Project Completion by Start Date for Electrical Equipment Installation**


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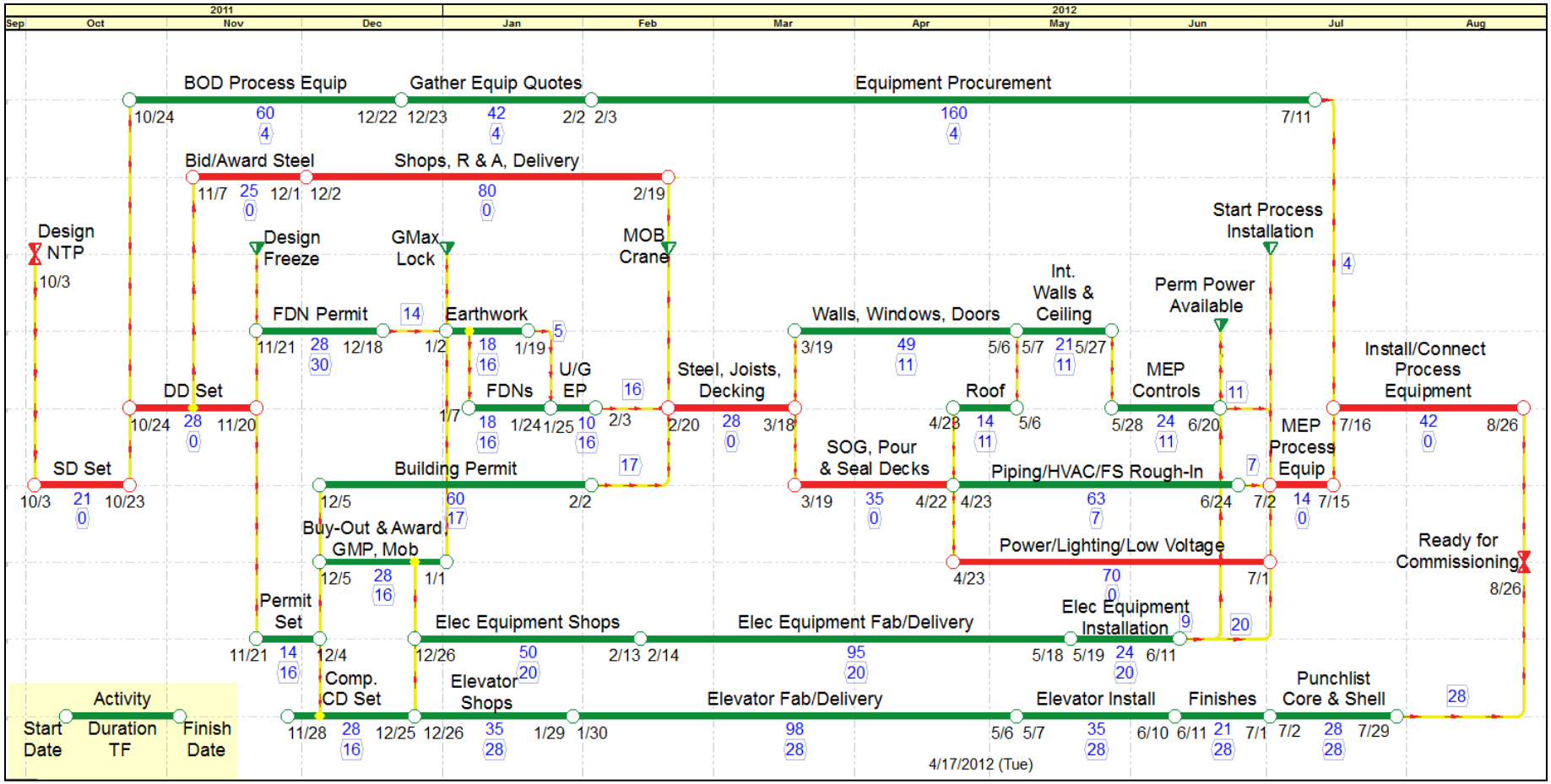



**Figure 5 – Base-Case Scenario Using Early Dates**



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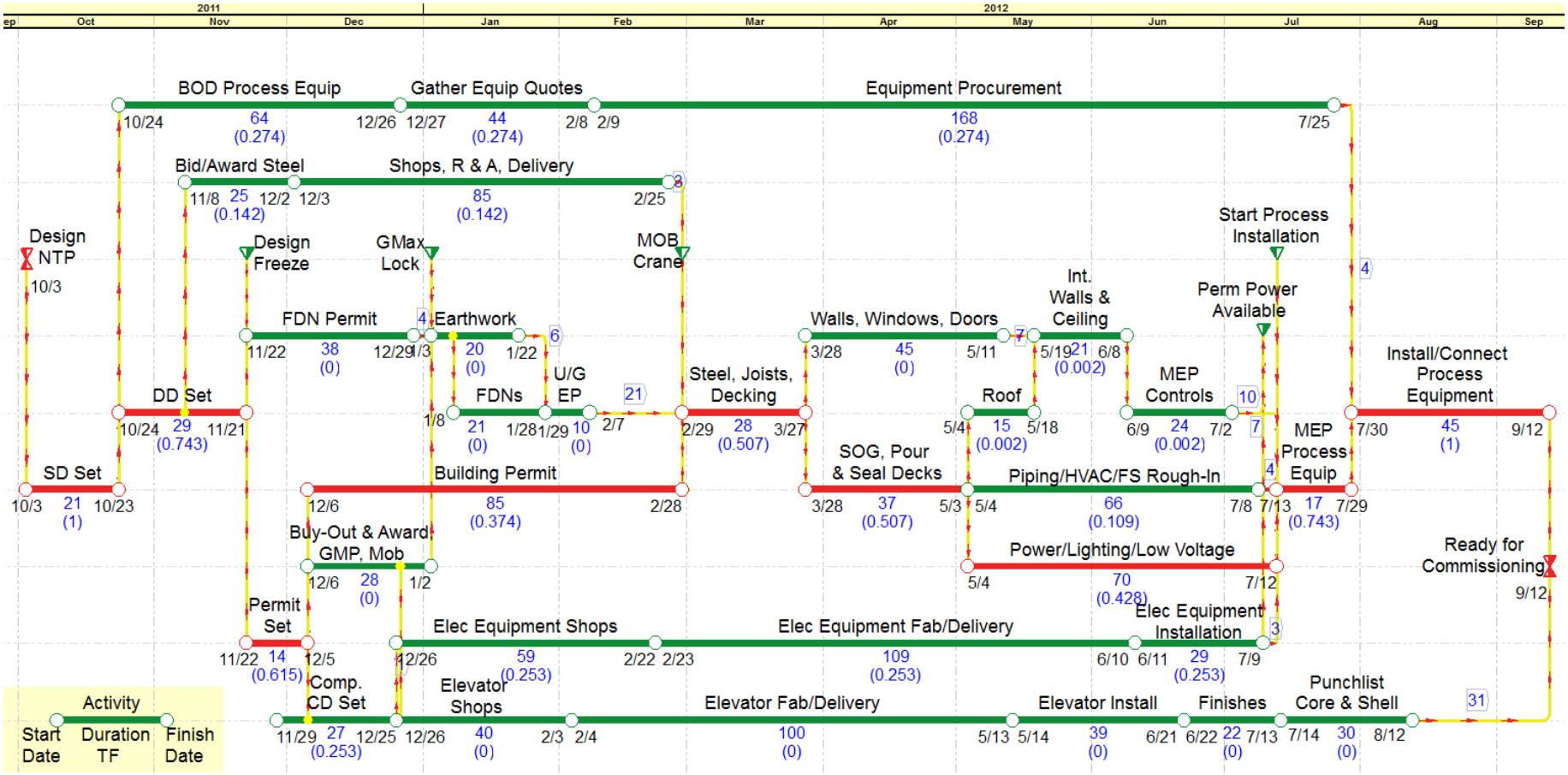



**Figure 6 – Criticality Indices for Base-Case Scenario**



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| Activity | Distribution |
|---|---|
| **Bid/Award Steel** | [20,25,30] |
| **BOD Process Equip** | [50,65,75] |
| **Building Permit** | [60,80,120] |
| **Buy-Out & Award, GMP, Mob** | 28 |
| **Comp. CD Set** | [25,28,28] |
| **DD Set** | [26,28,32] |
| **Earthwork** | [18,20,22] |
| **Elec Equipment Installation** | [22,30,35] |
| **Elec Equipment Fab/Delivery** | [85,105,140] |
| **Elec Equipment Shops** | [45,60,70] |
| **Elevator Shops** | [35,40,45] |
| **Elevator Fab/Delivery** | [90,100,110] |
| **Elevator Install** | [30,40,45] |
| **Equipment Procurement** | [150,160,200] |
| **FDN Permit** | [22,35,60] |
| **FDNs** | [18,20,25] |
| **Finishes** | [20,22,25] |
| **Gather Equip Quotes** | [40,42,50] |
| **Install/Connect Process Equipment** | [38,46,50] |
| **Int. Walls & Ceiling** | [18,21,25] |
| **MEP Controls** | [18,25,29] |
| **MEP Process Equip** | [14,16,20] |
| **Permit Set** | [13,14,15] |
| **Piping/HVAC/FS Rough-In** | [60,65,75] |
| **Power/Lighting/Low Voltage** | [65,70,75] |
| **Punch List Core & Shell** | [20,30,40] |
| **Roof** | [12,15,18] |
| **SD Set** | [20,21,22] |
| **Shops, R & A, Delivery** | [75,85,95] |
| **SOG, Pour & Seal Decks** | [35,37,38] |
| **Steel, Joists, Decking** | [25,28,32] |
| **U/G EP** | [8,10,12] |
| **Walls, Windows, Doors** | [40,45,50] |

**Table 1 – Base-Case Three-Point Estimates for Durations**

## Conclusion

The authors identify a significant limitation with CPM-based simulation approaches, which have become increasing popular over the past few decades. Using a case study, they also demonstrate the optimistic bias introduced by the early-dates limitation in CPM-based


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simulations. A GPM-based simulation approach was then described to model floating and pacing decisions, which are commonly made on real-world projects. GPM algorithms provide the ability to schedule activities on planned dates, making them inherently suitable for modeling floating and pacing scenarios. As such, this ability provides a significant improvement over the CPM-based approach as it allows the model to account for the impact of floating and pacing on merge risk and more realistically represents the actual system. The results of the case study illustrate how the early-date scenario overestimates the confidence in project completion probability and estimates the P80 date to be five days before the required completion date. However, after floating was introduced in the model for just three activities off the deterministic critical path, the P80 date pushed past the required completion date by one day, thereby predicting a probable delay in project completion. A combined floating and pacing scenario, with an additional activity allowed to pace, pushes the P80 date further out and predicts a five-day delay to the project.

An approach was also demonstrated to devise an all-floating scenario that develops the pessimistic project completion distribution curve. The base scenario (all early dates) and the all-floating scenario together form an envelope that encloses all possible scenarios for floating, with the assumption that no activity is floated beyond its then-available float. This envelope can be used to select a target completion date, analyze the potential for delays in the network, and, accordingly, allow any floating and pacing decisions to strategically control project progress.

The case study demonstrates that while floating and pacing decisions were made off the deterministic critical path, the underlying uncertainty in the remaining network resulted in a delay to the project completion date. This paper further presents a method to analyze schedule simulation results to understand and develop safe-float use by calculating the latest start date for every activity for which the calculation does not cause a delay in the project completion date. As a result, the decision to float or pace an activity when executing a project can be limited in use (i.e., only to the extent the amount of float used is not likely to impact the project completion date).

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