Proceedings of the 2016 Winter Simulation Conference
T. M. K. Roeder, P. I. Frazier, R. Szechtman, E. Zhou, T. Huschka, and S. E. Chick, eds.

EVALUATING PERFORMANCE OF CRITICAL CHAIN PROJECT MANAGEMENT TO MITIGATE DELAYS BASED ON DIFFERENT SCHEDULE NETWORK COMPLEXITIES

Yi Su
Gunnar Lucko
Richard C. Thompson, Jr.

Construction Engineering and Management Program
Department of Civil Engineering
Catholic University of America
Washington, DC 20064, USA

ABSTRACT

The *Critical Chain Project Management* (CCPM) method uses both project and feeder buffers in network schedules to act as cushions that absorb delays. These buffers are periods that are placed at the ends of critical or non-critical paths within the schedule. But how CCPM performs for probabilistic schedules has barely been studied systematically. It is hypothesized that the complexity of the networks influences how efficiently allocated buffers can fulfill their protective role. This paper therefore explores the relationship between complexity indices and the delay-mitigating performance of CCPM. Its contribution to the body of knowledge is twofold: First, schedule network complexity indices are reviewed and a schedule network graphing module is developed, which identifies the critical chain and buffer locations. Second, CCPM is applied to networks of different complexity with probabilistic durations. Their performance is measured in Monte Carlo simulations to evaluate the efficacy of buffer allocation under various different scenarios.

1 INTRODUCTION

Project delays affect all participants in the construction industry. Owners lose profits by receiving their projects with delayed completion dates, which means an inability to generate income to repay bank loans and earn a profit as planned. Contractors also seek to avoid such delays, because they would be charged liquidated damages by their owners. For material suppliers, subcontractors, and also laborers, delays will decrease their reputation and could eventually cause them to lose their work. Thus research on delays and how to mitigate their impacts is vital in construction management. Risk as a key delay cause is inherent in all projects to varying degrees and therefore every planning method should consider it. In the literature, CCPM is an approach to mitigate time impacts by allocating buffers at specific locations in a schedule. It is designed to absorb negative effects of delays. But its desired performance of protecting projects from random delays has not been systematically evaluated. This paper presents a method to validate CCPM and similar approaches to mitigate time impacts via schedule simulations with different levels of complexity.

2 LITERATURE REVIEW

2.1 Delays in Construction Practice

Construction projects unfortunately suffer from a noteworthy rate of delays in their schedules, as studies have shown in many countries for a diverse range of project types. Many studies have explored the factors that could contribute to delays, e.g. Larsen *et al.* 2015 or Gündüz *et al.* (2013), but they have essentially resorted to distilling lists of categorized causative factors from the managerial environment instead of establishing and testing preventive methods. Such listings and rankings have remained explanatory, while analyses of delay events for claims purposes (e.g. Braimah 2014) have been retrospective, not preventive.

Fewer studies have provided explicit percentage ranges of overruns, perhaps due to the difficulty of obtaining sufficient valid data, and if so, they focused typically more on cost than on time, e.g. Flyvbjerg *et al.* 2003. Nevertheless, valuable studies exist that have quantified the problem of time overruns in construction schedules. For example, Meng (2012) found that 35.2% of 105 British projects were time-delayed (cost and quality were less severe), with some variability due to owner-contractor partnering arrangements and an average overrun between 16-17% of the planned duration. Acharya *et al.* (2006) identified 65.5% of 208 Korean projects from different industry sector; of these 7.0% were up to 10% late, 14.8% up to 25%, 23.4% up to 50% late; the rest even more. Thomas *et al.* (2006) listed 20.9% of 713 U.S. highway projects as delayed in their Transportation Research Board report. In light of such prevalent delays across the construction industry, research should prioritize proactive delay prevention.

Throughout studies in the literature, as well as in this research, it is assumed that each project has one unique baseline schedule that is mutually agreed upon before its start, so that any delays can be quantified absolutely. Delays may occur in two forms – extensions within the duration of an ongoing activity or shifts in the start of a not-yet-started activity due to a delayed predecessor. This research will focus on the former, because shifts of activities can typically be explained as a ripple effect of extended predecessors.

2.2 Approaches to Protect Schedules

Approaches with which practitioners attempt to protect their schedules include both informal and formal ones. The former are intuitive and empirical rules-of-thumb that schedulers may apply. But depending on experience makes such approaches very subjective. More deliberate approaches exist, but interestingly the most widely publicized approach, CCPM appears to be formalized, but at its core relies upon a series of subjective assumptions as follows (Goldratt 1997), which Stratton (2009) critiqued as oversimplification. This can be attributed in part to a human tendency to keep the risk low and assign 'safe' (i.e. pessimistic) estimated durations when planning one's activities (Lucko *et al.* 2016), which CCPM seeks to eradicate:

- Baseline schedules are treated with suspicion, because it is assumed that their creator has already generously inflated durations in favor of the general contractor who is responsible for delivering the project and subcontractors who must perform individual activities (Herroelen and Leus 2001);
- Said inflation is assumed to have increased the initial average durations (i.e. a 50% probability of finishing on time) to pessimistic duration estimates (i.e. a 100% probability of finishing on time);
- Such inflation is assumed implicitly to be caused by a possible psychological need of schedulers to minimize risk with conservative duration estimates, and of their companies to not understate the baseline total project duration. This facilitates the ability to earn an early completion bonus. Per the saying 'work expands to fill the time that it is given', a project may thus expand to finish just before the contractual deadline, but not significantly earlier, even it were technically possible;
- It is assumed that schedulers derive an 'urgency' of the project based on its allowable period from notice to proceed to contractual deadline and select the planned means and methods accordingly.

Based on these assumptions, CCPM cuts all initial durations in half and adds half of the sum of these cuts back as one so-called *project buffer* (PB) at the end of the critical path (critical chain). An analogous '50% rule' is also applied to each non-critical side path, where an equivalent *feeder buffer* (FB) is placed directly before it merges into the critical chain. At first glance, buffers resemble float. Float occurs in network schedules that are calculated with the *Critical Path Method* (CPM), which adds durations along paths of dependency, propagates maxima if several paths merge, and identifies the longest path as critical. Both seek to generate a schedule whose internal protection makes it resilient against the negative impacts of delays. But buffers and float differ in whether their creation is purposeful or not (Lucko *et al.* 2016).

The use of buffers is explicitly allowed in CCPM. Since the initial flexibility is reduced, aggregated, and returned, all activities on a preceding path (chain) share it via a 'first come, first served' policy. This resembles total float, which is shared along a non-critical path in CPM. However, its actual consumption by delayed activities is not tracked in detail, it may be unfair to activities that are delayed later during the project and find the buffer already depleted, and it is unclear how well this simplistic approach performs.

Tenera and Machado (2007) suggested sizing the project and feeder buffers with a software-based simulation for a user-selected confidence level. Dividing individual buffers into three levels of severity and color-coding them green, yellow, and red was described by Dilmaghani (2008), but not generalized from such colored zones of equal width toward mathematically classifying how buffers protect individual paths and the entire project. The focus of such "Fever Chart" (*ibid.*, p. 22) was on tracking the buffer consumption (input), not mitigating delays (output). It was critiqued that "CCPM, however, does not provide a scientific basis for determining the buffer size" (*ibid.* p. 26), much less a measure of its efficacy to achieve its stated goal of protecting against delays. A related study (Verhoef 2009) reused the triple coloration, but also did not formalize any measure of buffer performance. Zhang *et al.* (2014) determined a recommended PB based on resource utilization and flexibility to move activity starts, considering the difference from 50% to 90% completion probability. Again, this focused on inputs, rather than outputs.

2.3 Schedule Network Complexity Indices

Network complexity measurement is part of graph theory research. Based on whether links (arcs in the graph) that represents a relationship between activities (nodes in the graph) has a direction, graphs are categorized as directed or undirected. Moreover, based on whether logic loops are allowed within the links, it is classified cyclic or acyclic. The construction "project network usually falls under a special category in graph theory called directed acyclic graph" (Nassar and Hegab 2006, p. 557). The complexity of a schedule network "indicates high interconnection between activities" and can be reflected by many factors such as "the number of activities, the level of detail, and the shape of the project network" (*ibid.*, p. 554). While various such indices exist in the literature, two basic ones are selected for this research.

The first index, *density*, is defined as the ratio of existing versus all possible links (Lancichinetti *et al.* 2010). Suppose a schedule has a total of n activities. The maximum number of all possible links is $n \times (n - 1)/2$, since n possibilities exist to select a start node and n - 1 possibilities to select a finish node from remaining activities. Yet $n \times (n - 1)$ double counts an activity that is both the start and finish node for another activity e.g. {A-B} and {B-A}. Therefore it is divided by two to remove that redundancy. Density is "defined as the number of precedence relations (including the transitive ones[,] but not including the arcs connecting the dummy start or end activity) divided by the theoretical maximum number of precedence relations [$n \times (n - 1)/2$], where n denotes the number of nondummy activities in the network" (Demeulemeester *et al.* 2003, p. 19) and is sometimes called *order strength* (OS). The second index is the *restrictiveness estimator* (RT) as was originally defined by Thesen (1977) in a theoretical derivation. It assumes a schedule with $n + 2$ activities (with dummy start and finish) and a known *reachability matrix* R. The matrix $R = [r_{ij}]_{n \times n}$ is defined as $r_{ij} = 1$ if activities i and j are reachable (connected by a path), else $r_{ij} = 0$ (Schwindt 1995). First, calculate the number of disjunctive arcs n_d, i.e. activities without common precedence relations in the schedule. Second, take the ratio of actual n_d and maximum possible number $n_d^{\max} = n \times (n - 1) / 2$ of disjunctive arcs. One minus this ratio is RT per Equation 2, where the number of possible links in the upper right triangle of R gives $(1 + 2 + \ldots + (n + 2))/2 = (n + 2) \times (n + 3)/2$. The value of RT is within the interval [0,1]. It equals 0 in a perfect parallel digraph (directed graph) and is 1 in a serial digraph (Schwindt 1995). Note that "[r]edundant arcs have no effect on RT, since it is based on the reachability matrix (the closure of the connectivity matrix)" (Latva-Koivisto 2001, p. 16). Overall, both indices seek to capture complexity, but RT incorporates a more explicit representation of the structure.

$$OS = \frac{number\ of\ \ predecence\ \ relations}{n \cdot (n\text{ - }1)/2} \tag{1}$$

$$RT = 1 - \frac{n_d}{n_d^{\max}} = 1 - \frac{(1+2+\ldots+(n+2))/2 - \sum_{i,j \in V} r_{ij}}{n \cdot (n-1)/2} = \frac{2 \cdot \sum_{i,j \in V} r_{ij} - 6 \cdot (n+1)}{n \cdot (n-1)} \tag{2}$$

2.4 Research Objectives

Two **Research Objectives** are set to address the Research Question of measuring performance of CCPM:

- Develop a topological approach that handles the concepts of CCPM, including the allocation of project and feeder buffers, and review and implement complexity indices that have been created for networks;
- Vary the input of example schedules in terms of complexity and in a Monte Carlo simulation evaluate the performance of CCPM regarding its ability to protect schedules against impacts of random delays.

3 METHODOLOGY

The methodology for this research is best represented as a flowchart with the four modules per Figure 1. Its modules are CPM, network graphing, CCPM, and Monte Carlo simulation, respectively. The CPM module starts with basic input data for the schedule network, including names, probability distributions of durations, and sequential relations of activities. Both mode (most likely) duration and random duration are taken into account in the CPM calculation. Column ID is a byproduct of CPM. It represents the *sequence step* of each activity in the schedule. Forward and backward passes are calculated iteratively in the order of the column ID. It is also used when plotting the network of the schedule, wherein activities are parallel that share the same column ID per Figure 2. In the network graphing module, adjacency and reachability matrices are calculated from the sequential relationships between activities. By definition, the *adjacency matrix* $A = [a_{ij}]_{n \times n}$ is a $n \times n$ matrix, where n is the total number of activities and $a_{ij} = 1$ if activities i and j are *directly* connected (adjacent), else $a_{ij} = 0$ (Schwindt 1995). It has also been called dependency matrix (Maheswari *et al.* 2006). The adjacency matrix is more strict than the aforementioned reachability matrix.

Combined with the network density index, the network module outputs an activity-on-node (AON) network graph and its complexity indices. In the CCPM module, the CPM results are connected with PB and FBs. As has been described above, PB and FB are limits. A Monte Carlo simulation module evaluates the performance of CCPM. By comparing its randomized outputs of total project duration (i.e. final finish) and non-critical path finishes with PB and FBs, it is recorded whether the former has exceeded the PB limit and whether any of the latter has exceeded their FBs, and if such overrun occurs, by how much. This is displayed graphically in Figures 2 with intuitive traffic signal colors. Note that users can select any suitable probability distribution to perform this analysis, e.g. triangular, beta, and others. This topological approach has been implemented in MATLAB programming code and fulfills **Research Objective 1**.

4 VALIDATION

Two schedules are selected from the Project Scheduling Problem Library (PSPLIB) for validation. These schedules have significantly different sizes and complexities. While J301_10 contains 32 activities with a total project duration of 37 days, J901_10 has 92 activities and 87 days duration. Their complexity indices are calculated as density = 0.09 and RT = 0.42 (J301_10) versus density = 0.03 and RT = 0.25 (J901_10). The J301_10 is denser and more parallel, while J901_10 is less dense and more serial per Figures 2 and 3. It is assumed that their initial durations were derived consistently before being cut according to CCPM.

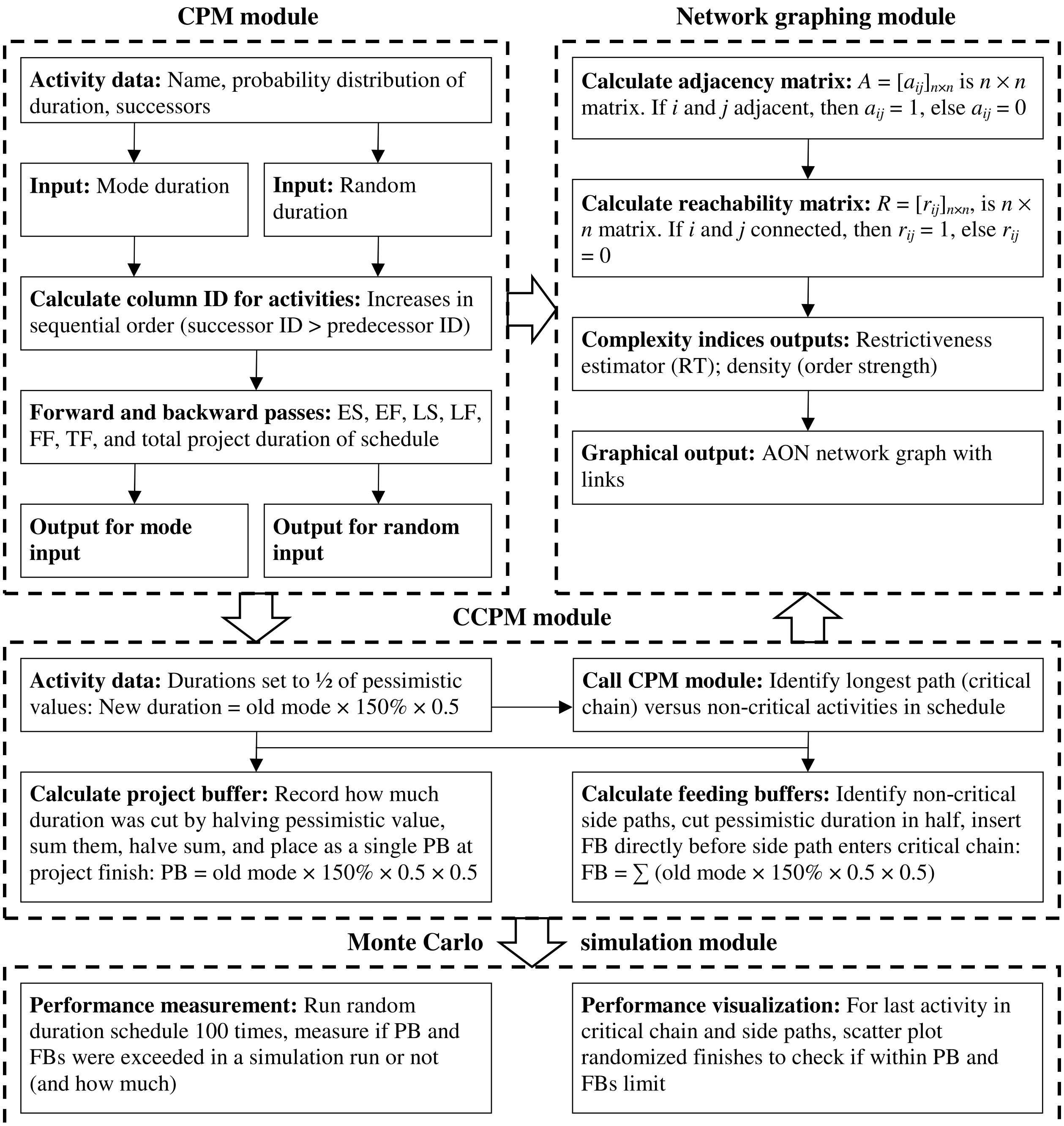

Figure 1: Flowchart of methodology.

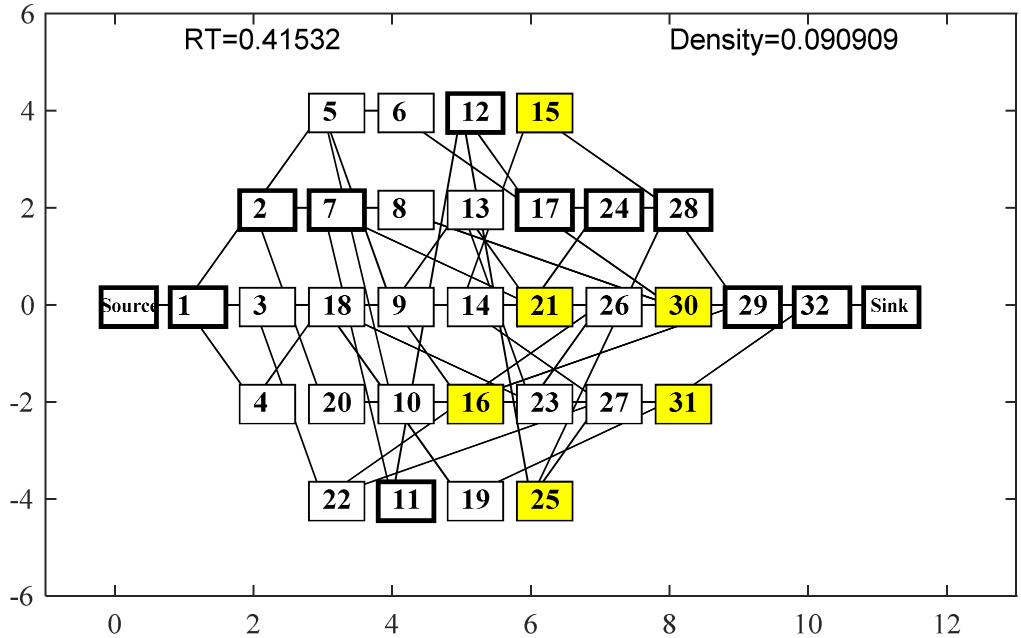

Figure 2: Network for J301_10 schedule.

To test the performance of CCPM with probabilistic durations, a stochastic behavior is assumed and both triangular and beta distributions are applied as the random duration input to the initial deterministic network schedule examples: The minimum, mode, and maximum limits of {90%, 100%, 150%} of the original PSPLIB duration are used in both cases. The goal is to measure if PB and FB are sufficient to protect from randomly occurring delays that may affect the project finish or the non-critical path finish.

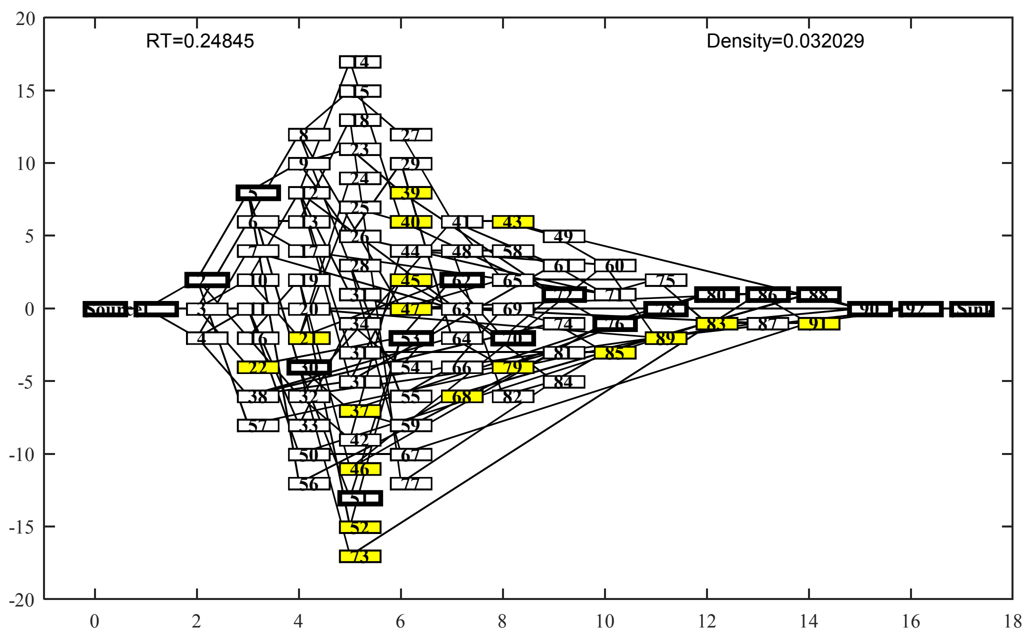

Figure 3: Network for J901_10 schedule.

5 DISCUSSION

The initial total project duration of the J301_10 schedule is 37 days. Per CCPM, the cut total duration is 37 × 150% × 0.5 = 27.75 days (first increased to an optimistic duration of 150%, which CCPM explicitly assumes the original scheduler has submitted, then rounded to 28 days) with PB = 0.5 × 27.75 = 13.875 days. Four colored vertical bars represent the PB cutoffs of the cut duration, plus an extra one-third, two-thirds, and three-thirds of PB at 2 × PB (28, black), 2.33 × PB (32, green), 2.66 × PB (37, yellow), and 3 × PB (42, red), respectively. Per CCPM the fixed total duration plus PB is 27.75 + 13.875 ≈ 42 days. The following scatterplots of Figures 4 and 5 show the relative performance of FB for activities that end a non-critical side path {15, 16, 21, 25, 30, 31} that are yellow in Figure 2. Each dot in the figures is one randomized simulation run for that activity. For clarity, the positive and negative performances are shown separately in Figures 4 and 5, respectively. The FB plots of Figures 4 and 5 have lower and upper limits of the latest start minus FB and latest finish plus FB for non-critical activities with FBs. Only non-critical activities {15, 30, 31}are fully protected by FB, which means that no overrun beyond the red bar occurs.

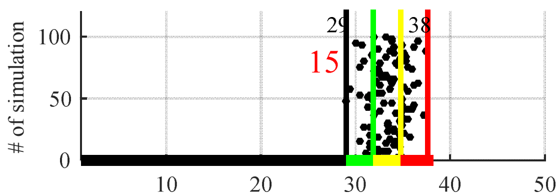

Figure 4a: FB for activity 15.

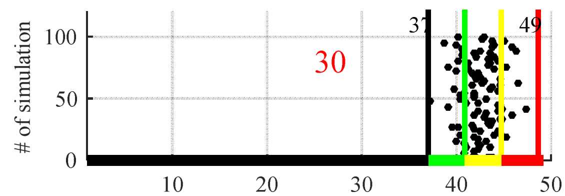

Figure 4b: FB for activity 30.

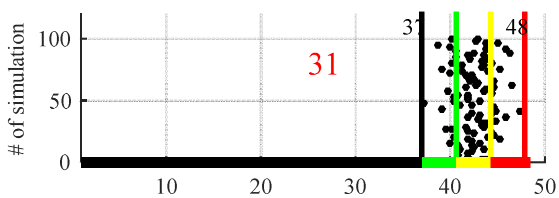

Figure 4c: FB for activity 31.

Figure 4: Positive FB and PB performances for J301_10 (Triangular).

The remaining non-critical activities are less protected, ranging from some overruns for {16, 21} to the right of the red bar in Figures 5a and 5b to falling nearly always beyond the buffered ranges for {25} in Figure 5c. Figure 5d shows the PB performance for the entire project. Here randomized total project durations fall past the red bar, so the PB has mostly failed to protect the projects in these simulation runs.

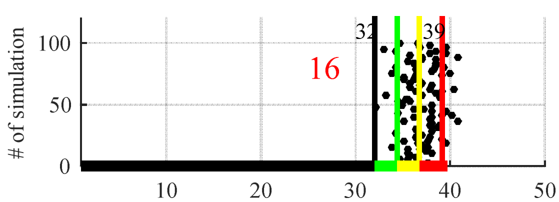

Figure 5a: FB for activity 16.

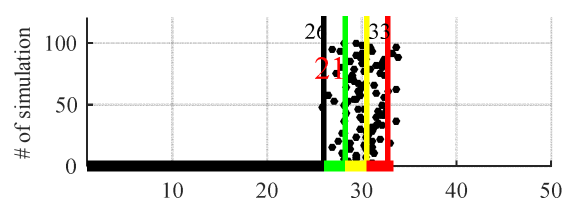

Figure 5b: FB for activity 21.

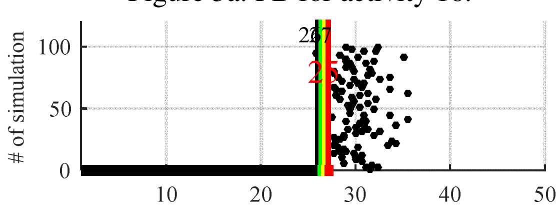

Figure 5c: FB for activity 25.

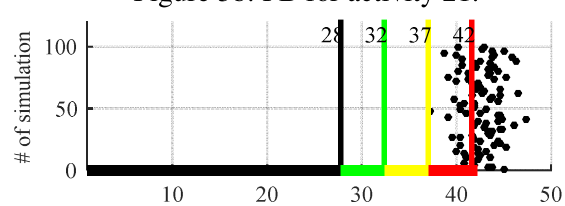

Figure 5d: PB for entire project.

Figure 5: Negative FB and PB performances for J301_10 (Triangular).

For the J901_10 schedule of Figures 6 and 7, the initial total project duration is 87 days and the cut duration is $87 \times 150\% \times 0.5 = 65.25$ days, with PB = 32.625 days. The black, green, yellow, and red bars are calculated as 65, 76, 87, and 98 days in analogy to the description of the previous example. In this larger schedule with 92 activities, the performance of CCPM is even less satisfactory. Figure 6 shows that only the non-critical activities {40, 45, 83, 91} are fully protected by FB, i.e. four of 17 activities = 24%.

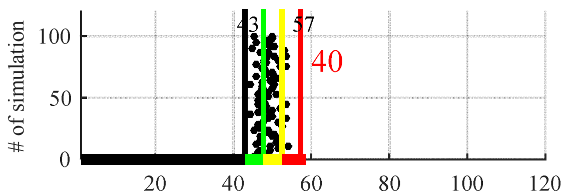

Figure 6a: FB for activity 40.

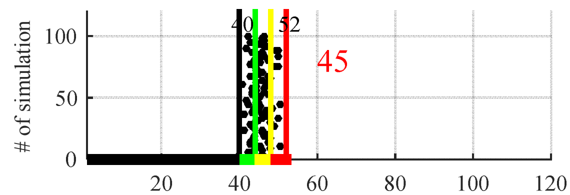

Figure 6b: FB for activity 45.

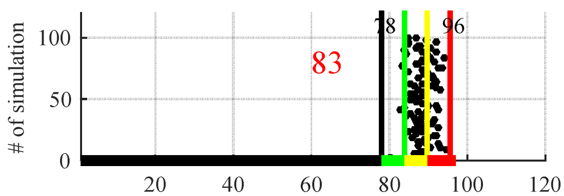

Figure 6c: FB for activity 83.

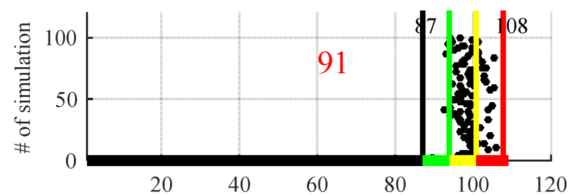

Figure 6d: FB for activity 91.

Figure 6: Positive PB and FB performances for J901_10 (Triangular)

Figure 7 shows the remaining 13 activities = 76% that are only insufficiently protected by FB. As can be seen, the performance ranges from slight overruns {e.g. 21, 22, 52} to severe cases {e.g. 37, 68, 73} in which CCPM largely fails to protect the critical path from delays in the respective non-critical side path. The much larger proportion of unsuccessful FB within this larger example compared to the smaller one is alarming and may result from its size that provides more opportunities for delays causing ripple effects. Figure 7n shows the PB performance for the entire project. Interestingly, a larger number of simulation results overrun the red bar for J301_10 that for J901_10, 74 versus 57 runs. While differences exist at the activity level, where a worse performance is found for the larger schedule, the overall ability of PB to protect the entire project is approximately equally poor. Note that both Figures 5d and 7n show that the entire delayed projects consistently exceed the green and yellow ranges and at best are in the red range.

Observations for the beta distribution are very similar to Figures 4 through 7 and excluded for brevity. In general, CCPM is found to function differently, but overall rather disappointingly, for the smaller and larger example with their different complexities. This applies to FB in the non-critical chains and PB in the critical chain. This analysis and comparison of different schedule s fulfills **Research Objective 2**.

6 CONCLUSION

Delay is a serious issue that plagues the construction industry and merits in-depth research. CCPM is an established but unproven methodology of inserting buffers to cushion delays that threaten critical and also non-critical activities. However, the method has remained a theoretical suggestion without much scientific analysis of its actual protective abilities. This paper therefore has established a formal systematic process with four modules to facilitate testing the performance of CCPM. Following the tenets of CCPM, the FB and PB have been calculated and inserted. Running Monte Carlo simulations with probabilistic duration distributions for a small and large schedule of different complexities from the PSPLIB collection, delays have been recorded *vis-à-vis* the provided buffers. Disappointingly, CCPM has been found to largely not live up to its promise, as both examples have incurred overruns, both for their non-critical and critical chains, both for triangular and beta distributions. Further research should study a larger set of examples and vary other factors, e.g. ranges of probability distributions, which may impact the overall performance.

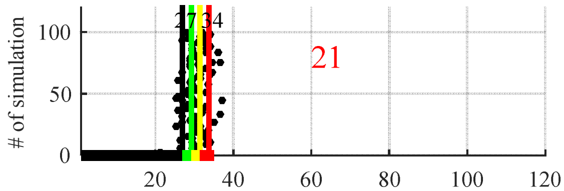

Figure 7a: FB for activity 21.

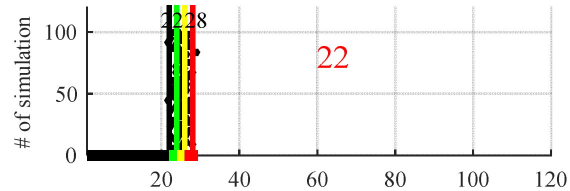

Figure 7b: FB for activity 22.

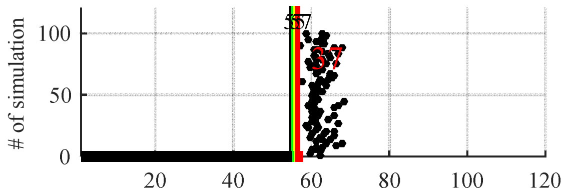

Figure 7c: FB for activity 37.

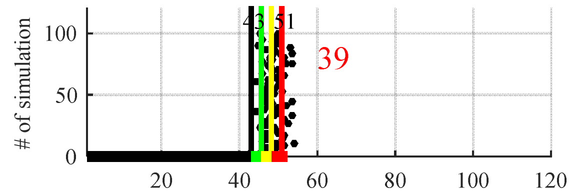

Figure 7d: FB for activity 39.

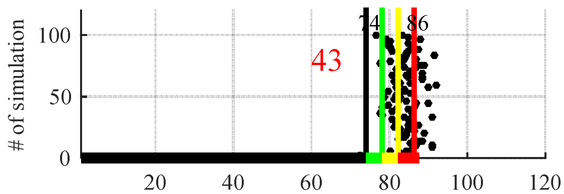

Figure 7e: FB for activity 43.

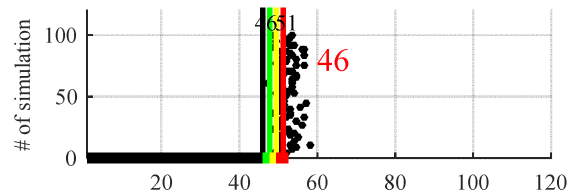

Figure 7f: FB for activity 46.

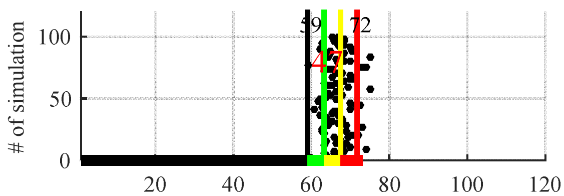

Figure 7g: FB for activity 47.

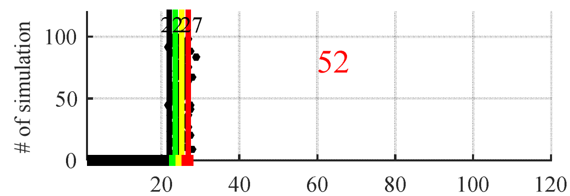

Figure 7h: FB for activity 52.

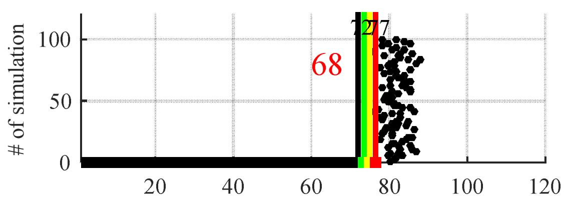

Figure 7i: FB for activity 68.

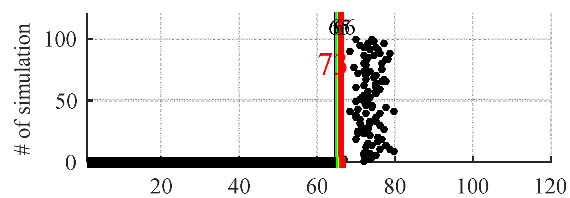

Figure 7j: FB for activity 73.

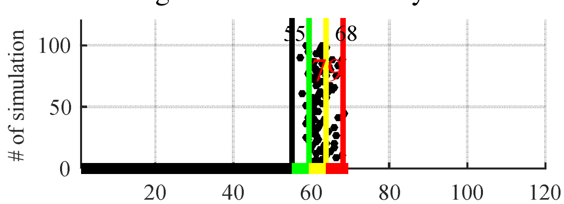

Figure 7k: FB for activity 79.

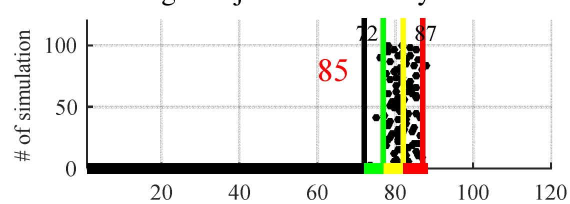

Figure 7l: FB for activity 85.

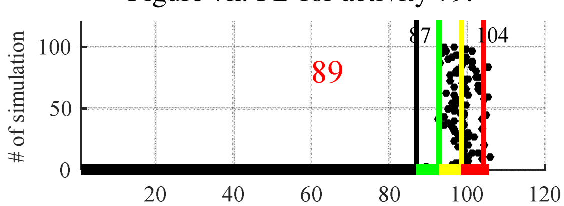

Figure 7m: FB for activity 89.

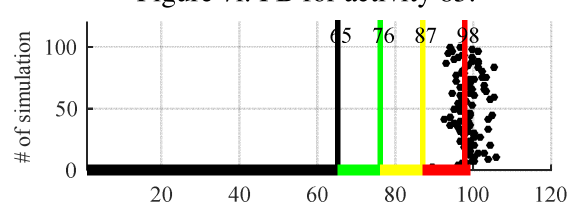

Figure 7n: PB for entire project.

Figure 7: Negative PB and FB performances for J901_10 (Triangular)

It is merited to examine how the intuitive key idea of CCPM, to strategically allocate buffers within network schedules, including where and how much, can be realized in a testable way (Lucko *et al.* 2016).

ACKNOWLEDGEMENTS

The support of the National Science Foundation (Grant CMMI-1265989) for portions of the work presented here is gratefully acknowledged. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily represent the views of the National Science Foundation.

REFERENCES

Acharya, N., Lee, Y., Kim, S., Lee, J. Kim, C. 2006. "Analysis of Construction Delay Factor: A Korean Perspective." *Proceedings of the 7th Asia Pacific Industrial Engineering and Management Systems Conference*, Bangkok, Thailand, December 17-20, 2006: 883-895.

Braimah, N. 2014. "Understanding Construction Delay Analysis and the Role of Preconstruction Programming." *Journal of Management in Engineering*, 30(5): 0742-597X/04014023(10).

Demeulemeester, E., Vanhoucke, M., Herroelen, W. 2003. "RanGen: A Random Network Generator for Activity-on-the-Node Networks." *Journal of Scheduling* 6(1): 17-38.

Dilmaghani, F. 2008. "Critical Chain Project Management (CCPM) at Bosch Security Systems (CCTV) Eindhoven: A Survey to Explore Improvement Opportunities in the Scheduling and Monitoring of Product Development Projects." M.S. thesis, School of Management and Governance, University of Twente, The Netherlands: 61 pp.

Flyvbjerg, B., Holm, M. K. S., Buhl, S. L. 2003. "How Common and How Large are Cost Overruns in Transport Infrastructure Projects?" *Transport Reviews*, 23(1): 71-88.

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.

Lancichinetti A, Kivelä M, Saramäki J, Fortunato, S. 2010. "Characterizing the Community structure of complex networks." *PLoS One* 5(8): 1-8.

Larsen, J. K., Shen, G. Q., Lindhard, S. M., Brunoe, T. D. 2015. "Factors Affecting Schedule Delay, Cost Overrun, and Quality Level in Public Construction Projects." *Journal of Management in Engineering* 32(1): 0742-597X/04015032(10).

Latva-Koivisto, A. M. 2011. "Finding a Complexity for Business Process Models." Research report, Systems Analysis Laboratory, Helsinki University of Technology, Finland: 26 pp.

Lucko, G., Su, Y. 2016. "Who Should Own Float? Mitigating Delays by Float Pre-Allocation." *Presented at the 2016 Construction CPM Conference*, ed. Plotnick, F. L., New Orleans, Louisiana, January 31 – February 5, 2016, Engineering and Property Management Consultants, Jenkintown, Pennsylvania: 8 pp.

Lucko, G., Thompson, R. C., Su, Y. 2016. "Simulating Balanced Allocation of Project Float to the Critical Path in Network Schedules." *Proceedings of the 2016 Construction Research Congress*, ed. Maldonado-Fortunet, F., San Juan, Puerto Rico, May 31 – June 2, 2016, American Society of Civil Engineers, Reston, Virginia: 10 pp.

Maheswari, J. U., Varghese, K., Sridharan, T. 2006. "Application of Dependency Structure Matrix for Activity Sequencing in Concurrent Engineering Projects." *Journal of Construction Engineering and Management* 132(5): 482-490.

Meng, X. 2012. "The Effect of Relationship Management on Project Performance in Construction." *International Journal of Project Management* 30(2): 188-198.

Nassar, K. M., Hegab, M. Y. 2006. "Developing a Complexity Measure for Project Schedules." *Journal of Construction Engineering and Management* 132(6): 554-561.

Schwindt, C. 1995. “ProGen/max: A New Problem Generator for Different Resource-Constrained Project Scheduling Problems with Minimal and Maximal Time Lags.” Report WIOR-449, Institut für Wirtschaftstheorie und Operations Research, Universität Karlsruhe, Germany: 53 pp.

Stratton, R. 2009. “Critical Chain Project Management Theory and Practice.” *Proceedings of Production and Operations Management Society 20th Annual International Conference*, ed. Hanna, M. Orlando, Florida, May 1-4, 2009, Miami, Florida: 31 pp.

Tenera, A., Machado, V. C. 2007. “Critical Chain Project Management: A New Approach for Time Buffer Sizing.” *Proceedings of the Industrial Engineering Research Conference*, eds. Bayraksan, G., Lin, W., Son, Y., Wysk, R., Nashville, TN, May 19-23, 2007, Institute of Industrial Engineers, Norcross, Georgia: 475-480.

Thesen, A. 1977. “Measures of the Restrictiveness of Project Networks.” *Networks* 7(3): 193-208.

Thomas, H. R., Ellis, R. D., Sinha, S. K.. 2006. “Improving the Time Performance of Highway Construction Contracts.” Final report to National Cooperative Highway Research Program, Transportation Research Board of The National Academies, Washington, DC: 82 pp.

Verhoef, M. 2013. “Critical Chain Project Management.” M.P.M. thesis, University of Applied Sciences, Utrecht, The Netherlands: 187 pp.

Zhang, J., Song, X., Díaz, E. 2014. “Buffer Sizing of Critical Chain Based on Attribute Optimization.” *Concurrent Engineering: Research and Applications* 22(3): 253-264.

AUTHOR BIOGRAPHIES

YI SU is a Ph.D. student in the Construction Engineering and Management Program in the Department of Civil Engineering at The Catholic University of America. His research interests include using singularity functions to numerically model and analyze problems in construction management via accurate and efficient models of time, cost, and resource interactions to facilitate work progress in construction projects. Areas of application include especially cash flow management, where he has studied prompt payment discounts and unbalanced bidding, and resource management. His email is 61su@cua.edu.

GUNNAR LUCKO is Associate Professor of Civil Engineering and Director of the Construction Engineering and Management Program in the Department of Civil Engineering at Catholic University of America. His research interests include mathematical modeling, simulation, and analysis of schedule networks and linear schedules under theory-building research projects funded by the National Science Foundation, most recently investigating risk mitigation via float allocation, as well as construction equipment operations and economics, optimization techniques, and engineering education. He is a member of ASCE. His email is lucko@cua.edu and his website is located at http://faculty.cua.edu/lucko.

RICHARD C. THOMPSON, Jr. is postdoctoral associate in the Department of Civil Engineering at Catholic University of America. His doctoral research has analyzed the exposure and mitigation of risk in construction management by adapting suitable proven analogous theories from related areas like statistics, economics, and finance. He serves as an adjunct instructor at CUA. He has been Vice President of the Office of Risk Management and Technical Standards and Mid-Atlantic Region Director of Operations in the Planning Design and Development Group at an international design firm. He is a registered architect in several states with over 25 years of professional experience on over 150 projects of over $3 billion in value that he led as Architect, Project Manager, Director, or Market Sector Leader. He holds an M.B.A. from Cornell University, a Ph.D. and M.S.E. from CUA, an M.Arch. from the NewSchool of Architecture & Design, and a B.S. in Design from Arizona State University. His email is rcthompsonjr@verizon.net.