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A multi-objective probabilistic-based method to determine optimum allocation of time buffer in construction schedules

Mani Poshdar[a,*], Vicente A. González[b], Gary M. Raftery[b], Francisco Orozco[c], Guillermo G. Cabrera-Guerrero[d]

[a] Department of Built Environment Engineering, Auckland University of Technology, Private Bag 92006, Auckland 1142, New Zealand
[b] Department of Civil and Environmental Engineering, The University of Auckland, Private Bag 92019, Auckland 1142, New Zealand
[c] Engineering School, Universidad Panamericana, Campus Guadalajara, Mexico
[d] Pontificia Universidad Católica de Valparaíso, Chile

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ABSTRACT

The use of buffers as a production strategy entails establishing a balance between theory and practice. In the complex environment of construction projects, this balance establishment requires an optimization process. It involves multiple criteria necessary to project success. So far, the heuristics and analytics developed, either fail to provide a clear logic to solve the multi-objective problem or revolve only around the mathematical solutions. This research proposes a Multi-objective Probabilistic-Based Buffer Allocation method (MPBAL) based on a goal-seeking optimization approach that uses a visual presentation of the mathematical optimization results to involve the preference of the project decision-makers in the final solution. MPBAL was tested against the records of a bridge construction project. The results were compared to the findings from a numerical analysis obtained by an extensive Monte Carlo study. The comparison indicated the high quality of MPBAL optimization analysis, while it utilizes an approximate combinatorial analytic method to avoid the errors typical of the numerical analysis.

1. Introduction

Construction is a schedule-driven environment [6]. A schedule enables the manager to control the project performance that may be represented by time, cost, and quality [4,5,12]. In practice, the schedule is subject to a disturbance in the implementation phase originated by fluctuating flow of work and information [6,16]. Among the strategies adopted to shield a schedule against these disturbances, the use of buffers emerges as an effective solution [22]. Buffers can be implemented in the form of excess time (time buffer), extra work capacity (capacity buffer), or extra material stockpile (inventory buffer) [22]. While they can take different forms, buffers are often represented by time added to the project duration [6].

From a practical standpoint, a production system can hardly avoid the use of buffers to have throughput [13,49]. From a lean production standpoint, however, buffers are deemed as the non-adding value component of production (i.e. waste). Theoretically, lean suggests the minimization (or elimination) of buffers [22,49]. Thus, a dichotomy exists between the theoretical and the practical implications of using buffers in projects. In order to alleviate this tension, a state of balance in the buffer allocation process is required that involves an optimization process [16,37]. An optimized buffer allocation must address two challenges [7,36]: 1) finding the best spot in the system to add the buffer, and 2) finding the suitable size of the buffer to be added.

In construction, the buffer allocation takes place to satisfy more than one objective [12,23,47]. The set of objectives specified for a construction project may include a combination of criteria with a deterministic or stochastic nature. In many cases, these objectives are conflicting [12,16]. Therefore, a multi-objective optimization problem occurs when allocating buffers to a construction schedule, for which no unique solution exists to optimize all the desired objectives simultaneously. So far, a wide range of production tools and techniques has been developed to address the buffer allocation problem, which have mostly originated from the manufacturing industry [18,38]. The range includes a variety of heuristics that define a logical sequence of steps to be taken, which do not necessarily provide an optimized allocation solution [12]. These heuristics often use rough mathematical models as an abstraction of the real world that typically encounters

* Corresponding author.
E-mail addresses: mani.poshdar@aut.ac.nz (M. Poshdar), v.gonzalez@auckland.ac.nz (V.A. González), g.raftery@auckland.ac.nz (G.M. Raftery), forozco@up.edu.mx (F. Orozco), Guillermo.cabrera@pucv.cl (G.G. Cabrera-Guerrero).

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approximation errors [3,38,50]. They use probability functions for this modeling purpose in order to simplify the calculation process. However, subsequently, this process overlooks details such as the shape properties of the functions. There is also a plethora of methods that configure the models by utilizing simulation-based techniques. These simulation-based methods frequently involve numerical errors originated by their discretization process, computer round-off, iteration, and statistical sampling [10,35,38].

Furthermore, most of the heuristics and simulation-based methods determine a fixed, singular, and unique arrangement of buffers to protect the system, ignoring the necessity of involving the individual preference of the decision makers. In practice, each decision maker has a unique characteristic, which causes no single solution to be an ideal fit [38,52]. Therefore, a method is required that supports flexibility and provide a range of options for the possible buffer allocation scenarios.

This study proposes a Multi-objective Probabilistic-Based Buffer Allocation method (MPBAL) that presents a formulated approach to solve the allocation problem in the multi-objective environment of construction projects. It embeds a specific mathematical calculation technique that minimizes the approximation and numerical errors. MPBAL also utilizes visualization techniques that support the involvement of the individual preference of the decision makers. In this study, a three-phase research design is used that allows one to move from a problem situation to a definition of a multi-objective optimization technique for the complex environment of construction projects.

2. Research method

The following steps were undertaken to develop the research:

1. Conceptual phase: A broad exploratory literature review was carried out to understand state of the art in buffer allocation techniques in construction. In this phase, the criteria used to assess the success of a project, the decision-making logic that can be utilized in a multi-objective problem, the necessity, and the potential approaches to involve the personal judgment of the project decision makers were evaluated.
2. Methodological development phase: A goal-seeking approach was adopted to formulate the multi-objective problem. A numerical solution was developed in this regard that quantifies the project objectives. This quantification process allowed a mathematical formulation to take place, in order to determine the optimality level of any buffer allocation scenario. The mathematical optimization framework was complemented by integrating a suitable representation of the analyses in the form of tables and graphs that involve the decision makers' preference to choose the final buffer allocation solution. An operational structure was created that includes 12 stages to implement MPBAL in the scheduling process of a construction project.
3. Case study: An experimental test was undertaken to evaluate the working mechanism of MPBAL through its application to the records of a bridge construction project. The experiments also utilized Monte Carlo simulation as a reference to benchmark the performance of the proposed method.

3. Research scope and assumptions

The following assumptions were defined to develop this research:

1. An initial construction schedule (un-buffered baseline for the expected durations) is available for the project that includes precedence relationships and resource dependencies.
2. The resource dependency is possible to be represented on an *activity on arrow* (AoA) network.
3. Buffers in MPBAL are represented by the duration of the activities in excess of their original expected duration.
4. No task will start earlier than their planned start time.
5. The likely variability in duration of any construction activity can be reliably modeled using Probability Density Functions (PDFs). Poshdar, et al. [40] have discussed different aspects attributed to this assumption.
6. The resource availability issues can be included in the uncertainty of task durations. This assumption is supported by the discussion provided in Lambrechts, et al. [24]
7. The activity durations are independent. This independence is expected to be achieved by utilizing strategies that focus on control of commitments such as the Last Planner System.
8. The variability associated with production can be measured by the coefficient of variation (COV) of process duration [22]. The COV is defined by the ratio of the calculated standard deviation over the mean value.

4. Criteria to assess success of a construction schedule

Criteria for success in a project can be defined as the set of principles or standards by which the desired outcomes can be achieved within the project specification [11]. A review of the existing literature shows that the criteria of success for a construction schedule can be addressed by two broad categories:

Deterministic Criteria: They serve to indicate the ability of the planned schedule to achieve a set of deterministic objectives. Total project duration (make-span), cost, project earliness and tardiness, and net present value are among these criteria [12].

Stochastic Criteria: They are adopted to represent the probability to meet the intended objectives. The *Timely Project Completion Probability* (TPCP), and the *schedule stability* are two important stochastic criteria that have been used by researchers. TPCP refers to the probability of having a project completion time equal or earlier than the planned value. The schedule stability relates to the magnitude of the difference between the planned schedule and the actual scenario [21,47]. It could be associated with different state variables of the schedule. Van de Vonder, et al. [47] proposed a starting time criticality (STC) heuristic, in which the schedule stability was calculated using a weighted sum of the absolute differences between the planned start time and the actual start time of activities. Lamas and Demeulemeester [23] defined the schedule stability as the probability that all activities start precisely at their planned start time.

A high-quality schedule should meet a combination of both deterministic and stochastic criteria [12,23,47]. However, these two groups of objectives are typically conflicting. Improvement of the deterministic objectives has an adverse impact on the stochastic objectives and vice versa. This study focuses on four main criteria including total project time, project cost, TPCP and schedule stability. This selection is mainly based on the recognition they have received by the advanced studies in the scheduling research [12,21,23,45,47]. It represents a multi-objective optimization problem in which no unique solution exists that can simultaneously optimize every objective.

5. The logic of decision making in a multi-objective problem

The decision-making patterns in a multi-objective environment can be categorized into three basic groups [52]:

Simple ordering: This concept leads to *Pareto optimality*. It pursues finding a set of efficient solutions in which none of the objectives can be improved without worsening the other objectives. Pareto preference is based on the assumption that "more is better," with no other preference information. It is the simplest method to determine the decision-making preference.