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AN INCLUSIVE PROBABILISTIC BUFFER ALLOCATION METHOD

M. Poshdar[1] , V. A. González[2], Sheila Belayutham[3]

ABSTRACT

The use of buffers in construction presents a tension between theory and practice. From a lean theoretical standpoint, buffers represent waste while they are an elemental part of construction schedules in practice. As a result, a reasonable balance is required to be established between the undesirable waste created by overusing buffers, and high risk of time/cost overruns generated by the lack of buffers. The balanced allocation of buffers includes two main aspects: Determining the size and the location of buffers in the planned schedule. These two factors are significantly affected by the general scheduling policy undertaken to determine the start time of activities. Also, both factors are dependent on the selected set of objectives in the project. Traditional buffer allocation techniques in construction have been informal and often inconsistent in addressing the buffer balancing issues. In this paper, an Inclusive Probabilistic-based Buffer Allocation method (IPBAL) is proposed which applies a mathematically driven strategy to resolve the balanced state in using buffers in construction schedules. It suggests a solution for the multi-objective buffer allocation problem that also accounts for the general scheduling policy. Hence, the method enables shielding the project activities against variability that is one of the steps required to implement lean in construction.

KEYWORDS

Variability, Buffer, Time compression, Scheduling, Network analysis.

INTRODUCTION

The adverse effect of variability is a well-known problem in construction. It generates fluctuations in the flow of work and makes the system performance unstable. Lean construction advocates a strong link between improving project performance and effective variability management. In order to reduce the negative impact of variability and improve planning reliability, Ballard and Howell (1997) suggested to implement lean production in construction in three steps: shielding direct production from variation in the movement of information and materials through the production

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[1] MSc, PhD Candidate, Department of Civil and Environmental Engineering, The University of Auckland, Private Bag 92019, Auckland 1142, New Zealand (corresponding author). E-mail address: mpos814@aucklanduni.ac.nz

[2] PhD, Senior Lecturer, Department of Civil and Environmental Engineering, The University of Auckland, Private Bag 92019, Auckland 1142, New Zealand. E-mail: v.gonzalez@auckland.ac.nz

[3] MSc, PhD Candidate, Department of Civil and Environmental Engineering, The University of Auckland, Private Bag 92019, Auckland 1142, New Zealand. E-mail address: sbel594@aucklanduni.ac.nz

network (workflow); stabilizing the workflow by reducing the flow variation; and improving performance in downstream activities.

Undeniably, even the leanest production systems require a minimum size of buffers as a part of the shielding process (González and Alarcón, 2010). In practice, construction schedule, barely avoid the use of buffers. However, at the same time in Lean, the use of buffers represents waste. In order to resolve the tension between practice and theory, a balanced state is required to be established by allocating buffer in the system (González and Alarcón, 2010). A wide range of production concepts and techniques have been developed, particularly in manufacturing that address buffer allocation issue (Demeulemeester and Herroelen, 2002; González and Alarcón, 2010). However, in most cases, the methods tend to be either extremely simplistic or complex in nature. The simplistic methods ignore crucial details such as the effects of prolonging non-critical chains, and important shape characteristics of the variability model including skewness and kurtosis (Anklesaria and Drezner, 1986; Yang et al., 2008). Simultaneously the extensively complex procedures are time-consuming and impractical. Many of these issues can be addressed using simulation techniques. Nevertheless, the use of simulation in construction can face serious challenges such as knowledge acquisition, model development process, and the black box effect due to which the model is assessed only based on its final outcomes (Abourizk et al., 2011).

This research proposes an Inclusive Probabilistic Buffer Allocation method (IPBAL) that addresses the balanced state in the use of buffers. It contributes to shielding the construction activities that is the first step of the implementing lean construction suggested by Ballard and Howell (1994). The analyses in IPBAL are undertaken using standard construction information such as the expected time and cost of activities. A mathematically-driven strategy has been adopted to process the information. The whole process is streamlined to avoid complex or unrealistic assumptions commonly associated with allocating buffers in construction. This mathematical approach also helps to trace back the results and understand the intermediate outcomes, which can decrease the reported black box effects by simulation users.

RESEARCH BACKGROUND

One of the main characteristics of construction is its uncertain nature. Accordingly, an optimal construction schedule is expected to comply with the uncertain circumstances (Van De Vonder et al., 2006; König, 2011). The extent to which a planned schedule can meet the optimality objectives is determined by using a range of measures. The applied measures can be classified into two general groups:

The deterministic measures which indicate the ability of the planned schedule to achieve certain deterministic objectives such as the *total project duration* (makespan) and *total project cost*.

The stochastic measures which refer to the ability of the planned schedule to absorb distortions. For example the probability of having a *project completion time* equal to or earlier than the planned value (Timely Project Completion Probability-TPCP) and the magnitude of difference between the planned schedule and the actual scenario (schedule stability) (Van De Vonder et al., 2006; Herroelen, 2014).

A good quality schedule should meet a combination of the deterministic and stochastic objectives (Demeulemeester and Herroelen, 2002). Accordingly, any buffer allocation in the schedule should be completed with respect to the intended combination of objectives. A suitable buffer allocation method should consider two important aspects: location and size of buffers (Park and Peña-Mora, 2004). These two factors are significantly affected by the scheduling policy, put toward to deal with the variability effects. The two common scheduling policies in this regard are as follows (Demeulemeester and Herroelen, 2002; Herroelen, 2014):

- Activities start as soon as possible. CCPM advocates using this concept to speed up projects. It permits the schedule to take advantage of the early finish of the predecessors. Thus, the *stability within the schedule* will not be of a primary concern. The concept also is known as *Roadrunner mentality* or *semi-active timetabling*. This policy is denoted by TM1 in the rest of the paper.
- Activities will never start earlier than their planned start time. In contrast to TM1, the *schedule stability* is of high importance in this managerial strategy. The concept is also termed as *railway scheduling approach*. It will be denoted as TM2 in this paper.

As TM1 disregards the schedule stability, shielding the plan at activity level becomes irrelevant. Accordingly, only an integrated source of buffer will be supplied at the end of the planned schedule to protect the project as a whole. On the contrary, in TM2, the individual activities are expected to be adequately buffered and shielded against disruptions.

In this paper, an inclusive method is discussed that determines the optimum allocation of time buffer in a feasible construction schedule. The method takes into account the general scheduling policy while addressing the common deterministic and stochastic objectives adopted in the construction schedule. It determines the trade-off between the objectives that are typically conflicting, and presents the results in an easy to understand style. Hence, IPBAL tends to be simple, easy to follow and reusable that can facilitate its practical site application.

RESEARCH METHOD

The research has been conducted in two major phases:

Conceptual phase: A comprehensive review was undertaken to identify buffering experiences in different fields of science and technology. It explored the common objectives and measures used in construction schedules; the existing methods used to analyse stochastic performance of a construction network; and the available multi-objective analytic approaches.

Development phase: The IPBAL framework was developed to analyse the stochastic performance of activity networks using a consistent mathematical procedure. A combination of objectives is adopted that are quantified in IPBAL using the following deterministic and stochastic measures:

1. Two deterministic measures: expected completion time and total cost of the project.
2. Two stochastic measures: The likelihood of completing the project within the planned time (TPCP); and the difference between the planned values and the *safest probabilistic scenario* that can provide an indication of *schedule stability*. The *safest probabilistic scenario* refers to the shortest expected

scenario that can be met with a probability of 100%. This concept will be discussed further on.

At the final stage, a graphical presentation was created to display the results in a way that assists the interpretation and communication with project personnel.

RESEARCH ASSUMPTIONS

From the conceptual phase, the following assumptions were made in this study:

1. An initial construction schedule (un-buffered baseline for the expected durations) is provided that includes precedence relationships and resource dependencies. It is assumed that the resource dependency is possible to be thoroughly indicated in an *Activity on Arrow* (AoA).
2. The likely variability in activity duration can be reliably modelled using Probability Density Functions (PDFs).
3. Resource availability issue is possible to be converted into the uncertainty of tasks duration.
4. The duration of activities is independent of each other along the network.
5. Total cost of the project comprises of time-dependent direct costs and indirect costs plus the time-independent costs such as cost of materials:

   $$TPC = \left[\sum_{i=1}^{n} (DC_i . du_i) + IDC . du_p \right] + cte \qquad (1)$$

   TPC is total project cost; DC_i denotes the time-dependent part of direct cost at activity i; du_i is planned duration for activity i; IDC is the time-dependent part of indirect cost of project; du_p is the total duration of project; and cte is the time-independent parts of cost.
6. The quality of the product is one of the important factors in project success and is highly correlated with time and cost (Atkinson, 1999). IPBAL receives the estimations about the duration of activities from project personnel as an input to calculations. It is assumed that the estimates include the minimum time (and accordingly the cost) requirements to ensure an acceptable quality of the final product.

DESIGN OF BUFFERS USING IPBAL

IPBAL includes three consecutive modules. It starts with analyzing the stochastic performance of the project. Hence, IPBAL can evaluate and compare effects of the undertaken scheduling policies and different buffer locating and sizing scenarios on the deterministic and stochastic measures within its next two modules. The results are presented in a comparative graph that enables project decision makers to track interactions between the competitive objectives and find the best compromise between the buffer allocation solutions. Figure 1 presents the stages included within the framework.

MODULE A- NETWORK ANALYSIS (STAGES 1 TO 3)

The establishment of an efficient and accurate method to analyse project network and assess its stochastic performance is a prerequisite to obtaining a proper buffer design that can protect the system. IPBAL adopts a mathematical solution to analyse the expected variability in project performance. The analyses are developed using the information provided by the project personnel at stage 1.

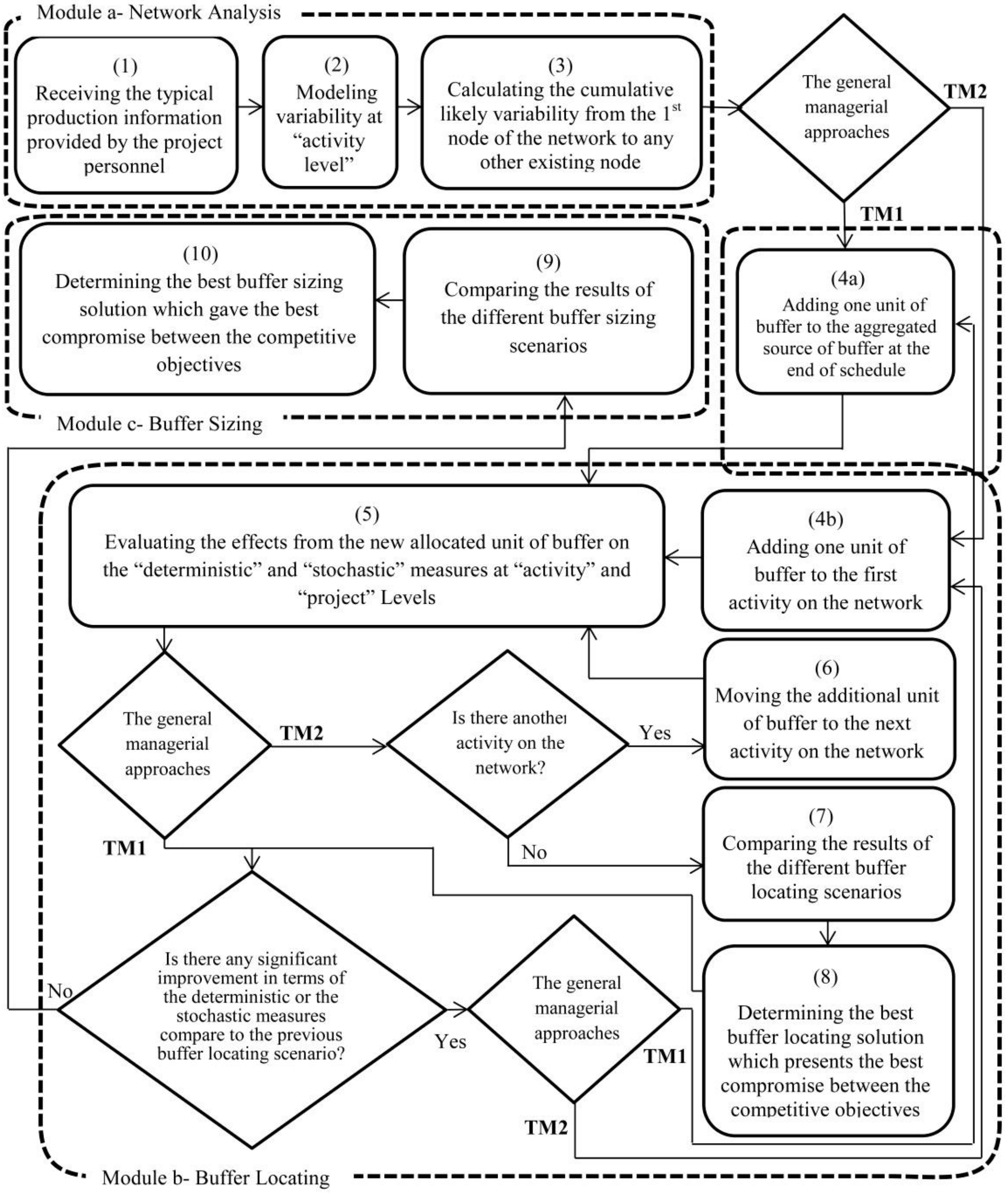

Figure 1. Modules and stages in IPBAL

The information includes the expected time range to complete the activity, and cost-related information such as the direct cost of each activity and the indirect costs of the project. The process of formulating the subjective knowledge from experts is a topic of discussion within Bayesian analysis which is beyond the scope of this paper. IPBAL is flexible in selecting any of the existing elicitation methods. The next two stages process the received data as follows:

In stage 2, the stochastic nature of variability at the activity level is captured using a Probability Density Functions (PDFs). In construction, the use of Beta PDF has been supported by a significant number of researchers. However, further research indicated that Beta PDF faces certain limitations in modelling highly variable processes. Accordingly, the Burr PDF has been suggested as a reliable complement for Beta PDF in such situations (Poshdar et al., 2014).

In stage 3, IPBAL combines the PDFs estimated at activity level based on the proposed method by Dodin (1985). In probability theory, the sum of two PDFs, which represent independent random variables, is calculated using *convolution* (Feller, 2008). However, the development of a distribution that can present the accumulated variability on a network of activities through *exact convolution* in most cases is a very complicated operation (Dodin, 1985; Demeulemeester and Herroelen, 2002). In the *approximate analytic approach* used in IPBAL, the continuous PDfs are discretized and combined in pairs (Dodin, 1985). The overall variability function at project level can progressively be calculated through repeating this algorithm over the network of activities.

To analyse the stochastic performance of the network, IPBAL associates each activity to three random variables:

1. The *time performance* of the individual activity that is characterized by a PDF as per stage 2 of the general framework,
2. The “start time” of the activity, which is governed by the *completion time* of its predecessor(s) on the network,
3. The *completion time* of the activity that is dependent on the two previous variables.

A *cumulative probabilistic index* (CPI) has been introduced to represent the probability functions of the *start time* (CPI_I) and the *completion time* (CPI_C) of activities. The CPI reflects the *accumulated likely variability* through the network, starting from the first node to any intended point on the designed AoA network. The *approximate analytic approach* is progressively developed over the project network. The final CPI_C calculated before the last node of the network represents the overall model of the projects variability.

MODULE B–BUFFER LOCATING PROCESS (STAGES 4A/4B TO 8)

As stated before, if the project follows scheduling policy TM1, the only included buffer will be located at the end of the designed schedule (Stage 4a). For cases in which the project adopts TM2, buffers are allocated to the individual activities. In such cases, IPBAL iteratively adds one unit of buffer to the system and checks the effects of the additional unit to different activities on the project network (stages 4b to 8). The effects are evaluated and compared based on the stated deterministic and stochastic measures of schedule optimality. This approach presents a development over the *Starting Time Criticality* (STC) (Van De Vonder et al., 2006) which uses the same iterative strategy. However, the mathematical approach undertaken to model variability at *Module a* (Figure 1), assists IPBAL to avoid the simplistic assumptions made in STC. It assumes the starting time of any activity is disturbed only by one of its predecessors at a time; and the disturbing predecessor starts at its original planned start time (Van De Vonder et al., 2006). Moreover, STC focuses only on schedule stability objective while IPBAL considers multiple objectives. The iterative procedure in IPBAL continues till no significant gains are made by the newly added unit of buffer in deterministic and stochastic objectives. A multi-layer calculation approach helps to evaluate the achievements of each adopted measures upon adding one unit of buffer to each activity on the network:

Layer 1- Calculating the expected project completion time (the first deterministic measure)

Expected completion time is calculated based on the expected durations provided at stage 1 of the general framework with the additional units of buffer assigned to that activity.

Layer 2- Determining the expected total cost of project (the second deterministic measure)

This layer uses the expected completion times at *activity* and *project* levels calculated in Layer 1, also to the cost-related information provided at stage 1 of the IPBAL framework applied in Eq.(1).

Layer 3- Calculating the likelihood of completing the project within the planned completion time (TPCP) (the first stochastic measure)

Given the expected project completion time calculated in layer 1, together with the project variability model determined at stage 3 of the general framework (the last calculated CPI_C), the likelihood of finishing within the expected completion time can be readily determined.

Layer 4- Calculating the Schedule Stability (the second stochastic measure)

As previously explained, a stability indicator is only of concern if the TM2 scheduling policy is undertaken. IPBAL estimates the schedule stability based on the difference between the planned values and the safest probabilistic scenarios. It represents the maximum probable difference between the planned and actual case. The stated differences can be calculated either in a time-wise scale, cost-wise scale or a combination of both. To bring all the differences to a dimensionless state, IPBAL expresses them in a relative form. Eq.(2) provides a combination of the values:

$$SI = I_{S1}.TSI + I_{S2}.CSI \tag{2}$$

SI is the total stability index that defines the difference between the planned and actual cases; TSI and CSI represent respectively time-wise and cost-wise stability indices; and I_{Si} is the importance factor for each of the defined indices that enable IPBAL to change the share of each TSI or CSI indices in total stability index ($0\% \leq I_{Si} \leq 100\%$).

In IPBAL, the time-wise stability is indicated by the average ratio between the *probability of meeting the planned completion time* and the *probability associated with the safest probabilistic scenario* [Eq.(3)]. The planned completion time for each activity is determined through the calculations in layer 1. The calculated CPI_C models at stage 3 of the general framework provide the probability of meeting the planned time.

Simultaneously, the safest probabilistic scenario is defined as the earliest completion time with its cumulative probability in the proximity of 100% (Figure 2). As for the second assumption of this study, each model contains a point of time after which the associated probability of meeting the plan will stay within the proximity of 100%. Therefore, the calculations of the TSI turns into calculating the average value of the individual stability indices.

$$TSI = \sum_{i=1}^{n} TI_i \Big/ N \tag{3}$$

TI_i is the probability of meeting the designed *completion time* for activity i (Figure 2), and N is the total number of activities on the project network.

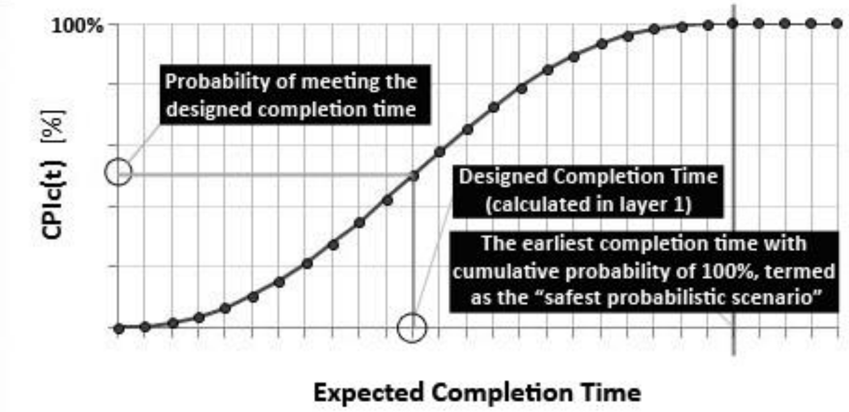

Figure 2. A typical CPI_c function presented in a cumulative format (stage 3)

IPBAL quantifies the cost-wise stability based on the maximum difference between the expected cost with the *total cost of the project* and *maximum probabilistic cost*. It is determined once the buffer locating process reaches stage 8 of the general framework. The *total cost of the project* is indicated in layer 2. The calculated time values for the safest probabilistic scenarios, explained in the previous section will be used in Eq.(1) to calculate the maximum probabilistic cost. The calculations undertaken for each buffer locating scenario are summarized in Eq.(4):

$$CSI = \frac{\left[\sum_{i=1}^{n}(DC_i.du_i) + IDC.du_p\right] + cte}{MaxCost} \qquad (4)$$

DC_i, du_i, IDC, du_p and cte are explained in Eq.(1); and MaxCost denotes the grand maximum of the accumulated costs within each buffer locating scenario.

Different feasible buffer locating scenarios can be quantified and compared by applying the four presented calculation layers. Hence, the buffer locating scenario that gives the best compromise between the adopted objectives can be identified in an iterative approach. This procedure continues until the newly added unit of buffer does not significantly improve any of the objective measures.

MODULE C- BUFFER SIZING PROCESS (STAGES 9 AND 10)

Once the buffer locating process has finished, the suitable size of buffer can be decided. Each additional unit of buffer is associated with a certain level of achievement in meeting the optimality objectives. The values achieved can be plotted on a graph that enables decision makers to track the trade-off between adopted objectives over the different size of buffers visually. Hence, the buffer sizes can be compared to determine a solution that provides the best compromise between the objectives. Figure 3 gives an example of such a comparative graph.

The graph includes four vertical axes where each represents one of the intended deterministic and stochastic objectives. The tick marks on the horizontal axis represent one unit of buffer added during each cycle of buffer locating process. The projection of the buffer size onto the resulted graphs for the adopted objectives determines the score level for each of the objectives. In the end, the final buffer size can be decided based on two major factors: Achieved level in meeting each of the objectives, and Efficiency of the additional units of buffers in terms of differential improvement that can be gained by the objective measures.

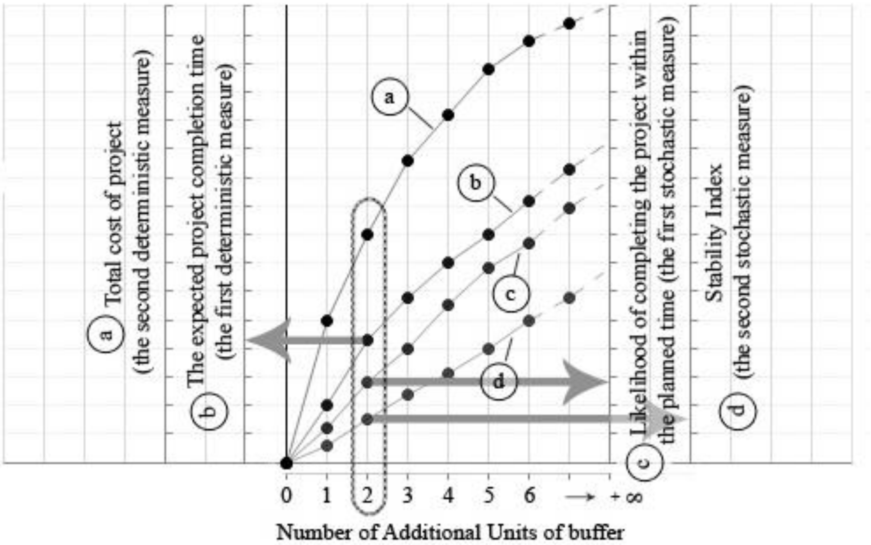

Figure 3 - Graphical presentation of the results

CONCLUSION

A mathematically-driven approach called inclusive probabilistic-based buffer allocation method (IPBAL) is proposed to establish a balance in the use of buffers in construction schedules. The buffer allocation designed provides an optimal solution to meet the common deterministic and stochastic scheduling objectives accounting for two possible policies of scheduling. The proposed method increases the efficiency in designing of the protection of project activities from variation in the workflow. The outcome of IPBAL can be implemented within the existing planning and control methods such as Last Planner System (LPS). It is expected that by enhancing the effectiveness of shielding design in the LPS along with its admitted capability in stabilizing the workflow through reducing the flow variation and improving the performance of the downstream activities, the overall efficiency of the planning and control system will be increased. For this purpose, IPBAL can support a systematic design of the activity protection in both the long-term and the medium-term plan.

IPBAL applies a progressive scheme in the calculation of variability models and buffer allocation that provides engineers with an easy to follow data processing architecture. Also, the presented steps for IPBAL offer a reusable framework that fits conventional practices in construction and can be adapted mostly to any construction work. Such advantages make the proposed framework appealing in practical aspects.

The method presents the analyses results in a comparative graph that offers a significant improvement over current buffering methods that typically rely on a single value solution for buffer allocation purposes. Decision making in IPBAL avoids such restrictions, by providing a range of solutions that can fulfil the deterministic and stochastic objectives in the buffered system. Two ongoing processes of *experimental tests of IPBAL through the records collected from a number of projects*, and *organizing a set of expert interviews* will help to evaluate the accuracy and practicality of the framework.

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