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A Risk-Oriented Buffer Allocation Model Based on Critical Chain Project Management

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Abstract

In this study, a multi-attribute buffer sizing method is proposed aimed at maximizing the robustness of the buffered schedule generated. The project attributes concerning the network complexity, flexibility criteria, criticality index and robustness measures are considered through the buffer sizing process. The methodology presented is based on the critical chain buffer management methodology, yet innovative metrics are presented to deal with the uncertainties associated with the critical and non-critical chains. The buffer sizing method proposed eliminates the previous limitations and attempts to economically determine the size of the feeding and project buffers. Additionally, a risk analysis is performed to examine the effects of external factors on buffer sizes. The weaknesses of the existing buffer sizing approaches were overcome in the critical chain project management, and a novel buffer sizing method was established based on internal and external risk aspects. A simulation experiment is conducted in order to prove the effectiveness of the method proposed. The computational results of implementing the method on a real case study specify that the method proposed generates more stable project plans at a lower cost, compared with those generated using traditional buffer sizing methods.

Keywords: *multi-attributes, critical chain buffer management, time buffers, risk analysis, root square error method*

1. Introduction

In the project management context, several research areas have been addressed by scholars, including project delay management (Bordoli and Baldwin, 1998; Braimah, 2013; González *et al*., 2013; Tsai and Yau, 2013), project disruption management (Kuster and Jannach, 2008; Kuster and Friedrich, 2009; Zhu, 2005; Zhu and Yu, 2004), project alignment and strategic management (Ansari *et al*., 2014; Kerzner, 2011) and critical chain buffer management (CC/BM) (Rand, 2000; Tenera and Cruz-Machado, 2007; Chun-chao, 2008; Vanhoucke, 2012). At initial stages of planning, project management endeavors to ensure a successful outcome (Hu and Demeulemeester, 2014). The promptly varying condition together with the increasing complication of projects make it more probable that project tasks have unreliable durations and extra costs. Therefore, one of the important problems in planning and management of real size projects is to generate a robust plan that guarantees the project makespan within the due date (Pich *et al*., 2002). Generally, the application of the existing methods may fail and lead to delays due to ignoring the project attributes. Providentially, the theory of critical chain project management (CC/PM) provides a flexible framework that accounts for a robust project schedule through the buffer sizing procedure. CC/PM was originally introduced by Goldratt as an application of the Theory of Constraints in the project management discipline. It delivers an efficient method of guaranteeing the timely performance of the project through introducing the idea of buffering projects, and it is regarded as a new approach to project control (Vanhoucke, 2016). The methodology uses three kinds of contingency buffers including Project Buffer (PB), Feeding Buffer (FB) and Resource Buffer (RB). The contingency buffers protect the initial plan against future disruptions (Russell *et al*., 2014).

The management of buffer consumption is also an operative technique in project controlling during the execution phase. Buffer management is a checking mechanism to monitor the key performance measures and take corrective actions when required (Vanhoucke, 2012). The main question is how to determine the size of the project and feeding buffers. In this regard, the application of the measurable metrics is crucial when generating a robust project schedule. The existing methods of CC/PM decide the time buffers heuristically, yet the project specifications are ignored. However, in real-world projects, the efficiency of the traditional buffer sizing methods is questioned. In other words, the validity

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Table 1. Research Taxonomy of Buffer Sizing Methods Based on CC/PM

Publication	Method name	Buffer sizing approach		Project specification												Outputs	
		Adaptive	Heuristic	NC	ND	RT	RP	DD	DF	RC	AC	F	CC	CR	CD	PB	FB
Roel (2003)	Activity-dependent float factor (ADFF)	-	√	-	-	-	-	-	-	-	-	√	-	-	-	√	-
Tukel and Eksioglu (2006)	Adaptive procedure with resource tightness (APRT)	√	-	-	-	√	-	-	-	-	-	-	-	-	-	√	-
	Adaptive procedure with density (APD)	√	-	-	√	-	-	-	-	-	-	-	-	-	-	√	-
Ma and Chen (2012)	Flexible buffer sizing approach	√	-	√	√	√	√	-	-	-		√	-	-	-	√	√
Bie and Zhang (2012)	Adaptive procedure With activity dependence (APAD)	√	-	-	-	-	-	√	√	-	-	-	-	-	-	√	-
Zhang and Diaz (2014)	Uffer sizing based on attribute optimization	√	-	√	-	√	√	-	-	√	√	-	-	-	-	√	-
Ma *et al.* (2014)	Improved buffer sizing	√	-	√	-	√	√	-	-	-	√	-	-	-	-	√	√
Iranmanesh *et al.* (2016)	-	√	-	-	√	-	-	-	-	-	-	-	-	-	-	√	√
Current study	Robust Multi-attribute buffer sizing	√	-	√	-	√	√	√	-	-	-	√	√	√	-	√	√

RT: Resource tightness; ND: Network density; NC: Network complexity; RP: Risk preference: DD: Dependence degree, DF: Dependence factor; RC: Resource cost index; AC:Activity cost index; F: Flexibility; CC: chain complexity; CR: chain robustness; CD: Chain dependency

of the buffer sizing methods is decisively dependent on the key features of a project. The extended buffer sizing methods must address the non-critical chains that are potentially critical during the project execution phase. The CC/PM methodology does not appropriately address such issues, yet this study suggests an improved methodology for efficient buffer sizing.

In the present study, a novel multi-attribute model has been proposed for the robust buffer sizing method, based on the CC/PM methodology. We extend the basic framework of the Root Square Error method (RSEM) to account for different sources of uncertainties. The contributions of the present study are threefold; primarily, new metrics are introduced to the process of buffer sizing approach. The time buffers are tuned according to the flexibility, complexity, robustness and criticality of the activities and the chains. In addition, the proposed buffer sizing method accounts for both critical and non-critical chains; and finally, the buffer sizing procedure incorporates a network-based risk assessment technique that analyzes the effects of external uncertainties on the buffer sizes.

The rest of the article is organized as follows: The state of the art is discussed in the next Section; the buffer sizing approach proposed is explained in Section 3; next, the confirmation procedure of real case studies are given in Section 4; the computational results are provided in Section 5; and finally, the conclusions and further researches are presented.

2. State of the Art

The existing buffer sizing methods can be classified into heuristic approaches such as the Cut and Paste Method (C&PM); statistical approaches like root square error method (RSEM), adaptive procedures with density (APD) and adaptive procedure with resource tightness (APRT). RSEM employs the statistical information of project activities to determine the size of the project buffer. In so doing, RSEM uses two estimates of the activity duration including a safe estimate and an average approximation. Then, it calculates the difference between the safe and average estimates and computes the sum of squares of the differences for all activities. The resulted value is regarded as the project buffer (Newbold, 1998). In order to better represent the singificance of the present research, the most relevant studies are categorized in Table 1. The literature is classified on the basis of the buffer sizing approach, the project features, the criteria used and the outputs.

Ma and Chen (2012) proposed an upgraded buffer sizing method that accounts for the project features. The buffer sizing method takes into consideration the network complexity measures, resource tightness metrics and risk preference to economically determine the sizes of the time buffers.

Liu and Peng (2012) introduced novel measures of the project network complexity to the buffer sizing approach. The validity of the approach proposed was proved through being compared with the existing buffer sizing methods using simulation experiments. Truc *et al.* (2012) developed a CC/PM framework on the basis of Max-Plus Linear algebra. The main decisions involved the position and size of time buffers for a large scale multi-project environment. The method takes into account the buffer sizing decisions for multi-project cases. Peng and Jiao (2012) addressed the multi-mode project scheduling modeling problem based on the critical chain methodology. In order to solve the multi-mode project scheduling problem, priority rules were applied. Peng and Huang (2013) developed an optimization model to produce a buffered schedule on the basis of CC/PM methodology. The approach focused on the extension of the

RSEM that incorporates the float time of the non-critical chains as feeding buffers. A modified Differential Evolution (DE) algorithm was proposed to solve the critical chain project scheduling problem. Ma *et al*. (2014) suggested a framework called PEST (Political, Economic, Social and Technological) to formulize the effects of external risks on the buffer allocation process. However, the internal effects of risk interactions on the buffer sizes have been ignored. Saihjpal and Singh (2014) proposed an extended method of Cut and Paste (C&P) technique. The method takes into consideration the float time factors in order to find a tradeoff between the project makespan and the schedule robustness. Hu and Demeulemeester (2014) proposed a buffer management model that takes into account the cost of corrective actions. The probability of on-time project completion was estimated as a performance measure. Ma *et al.* (2014) presented an improved buffer sizing method by integrating some techniques with resource leveling techniques. The buffer sizing method proposed generates multiple buffered plans that takes into account multiple activity execution modes. The robust project plans generated was intended to have a leveled resource usage profile to reach a tradeoff between project makespan and resource utilization. Zhang and Díaz (2014) proposed a buffer sizing method in order to improve the effectiveness of the buffered project plan. The project attributes including the complexity of the project network and resource metrics were used to determine the size of the project buffer. The conclusions drawn demonstrated that the buffer sizes obtained from the method proposed were smaller than the one generated by the C&P method; in other words, they were larger than the ones generated by RSEM method. Thus, the method proposed could economically determine the size of the buffers. Lee *et al.* (2003) applied stability conceptions to the buffer sizing procedure through a system dynamics model. The model proposed dynamically determines the time buffers. Van de Vonder *et al.* (2005) proposed a model in order to find a tradeoff between the quality robustness and solution robustness, using the buffer allocation technique in a CC/PM framework. The quality robustness was referred to the stability of the project makespan, while the solution robustness was measured as the deviation of the realized start times of activities from the planned times. Simulation experiments were accompanied to examine the effectiveness of the buffer sizing approach proposed as against the existing buffer insertion techniques. Tukel and Eksioglu (2006) analyzed the performance of different buffer sizing methods. They concluded that the adaptive approaches outperform the RSEM method. Ashtiani *et al.* (2007) addressed the critical chain project scheduling problem where the activity durations follow the lognormal distribution. A method was then proposed to determine the size of the project buffer.

Zhang *et al*. (2016) proposed a buffer sizing model based on the critical chain concept. A novel resource tightness metric was introduced to determine the project buffer size. Moreover, the information flow between activities was analyzed using the Design Structure Matrix (DSM). The model proposed could explain the insufficiencies of existing buffer sizing methods that only consider physical resource tightness and ignore information resource tightness. Poshdar *et al.* (2016) formulated a probabilistic buffer allocation method which incorporates the preferences of project manager about project makespan into a buffer sizing procedure. The model proposed could minimize the approximation errors through considering the main details of project activities, and also through maintaining such details when modeling at the project level. Zhang *et al.* (2016) addressed the critical chain project buffer sizing problem. It was demonstrated that the information flow interaction between activities is the key factor that affects the performance of buffer allocation methods. They utilized the resource tightness and network complexity to adjust the sizes of the time buffers. The computational results show that the project on time performance and the project buffer consumption rate were improved as against the traditional RSEM method. Hu *et al.* (2016) designed a dynamic buffer management approach using the Schedule Risk Analysis (SRA) method. The project monitoring framework was supported by the concept of activity crucially index. The value of crucially index triggers the corrective actions. Additionally, a dynamic setting was proposed for determining the action threshold according to the project progress along with the buffer consumption rate. Iranmanesh *et al.* (2016) proposed a buffer sizing model that addresses the uncertainty associated with project activities. The sizes of the time buffer were determined by a Post Density Factor (PDF) subject to the constrained resources, position of activity in a project network and risk factors. The performance of the buffer sizing method proposed was compared with the C&P method, RSEM, APRT and APD. Hu *et al.* (2016) designed an improved buffer management model that considered resource costs and schedule stability. The improved buffer allocation framework allows for resource allocation in order to minimize the resource costs expected. An order repair method was presented for project rescheduling when corrective actions were required. The empirical experiment proved the advantages of the project control mechanism proposed under different costs or resource availability information.

As reviewed above, the application risk assesment was ignored by the existing buffer sizing approaches. Risk management is the process of identifying and quantifying the probability of risks and also reducing the negative effects of risks to an acceptable degree (Jaafari, 2001). A proactive approach to risk management is to become organized for future potential risk events before the actual occurrence (Mehdizadeh, 2012). In the literature, there are different approaches to the quantitative risk analysis. Recent applications are concerned with the clustering and network-based risk analysis. The network-based risk analysis is based on matrix calculation and has high flexibility, ease of use and significant potential of analyzing critical levels of risks on different levels of Work Breakdown Structure (WBS). This approach formulates the risk interaction through the Design Structure Matrix (DSM) method introduced by Steward (1981). Marle and Vidal (2011) proposed the clustering analysis of risks in order to improve coordination in projects. Marle and Vidal (2013) conducted a clustering model that accounts for the role of stakeholders in the project risk assessment. Likewise, Marle, Vidal, and Bocquet (2013) designed a clustering model based on the interaction among risk factors. Recently, Fang and Marle (2015) carried out model-based risk analysis through a Risk Network Matrix (RNM).

As it can be seen, the majority of the existing researches have ignored the effects of project specifications and externals risks on the buffer sizing procedure. To the best of our knowledge, very few studies have addressed the multi-attribute buffer sizing procedure. Recent articles addressed the incorporation of new metrics that affect the size of the time buffers. Although the existing critical chain buffer sizing approaches addressed the project complexity and flexibility criteria, little attention has been paid to the study of the external uncertainty in the buffer sizing methods. The present study is aimed at providing an innovative approach to the critical chain project scheduling problem that overcomes the weaknesses of the existing adaptive methods based on novel chain performance indicators. The buffer sizing method developed incorporates the operational features of the project as well as the impacts of external risks on the stability of the project schedules generated. Thus, the present study makes the following contributions to the research community:

- Presenting a robust multi-attribute buffer sizing model based on the risk interaction analysis to economically determine the size of both the project and feeding buffers
- Introducing new indicators to measure the complexity, stability and robustness of critical and non-critical chains
- The next section provides the description of the multi-criteria buffer sizing method.

3. Improved Multi-attribute Buffer Sizing Method

In this section, the buffer sizing procedure is described in detail. The improved buffer sizing method develops the traditional RSEM through taking into account a multi-criteria decision framework. Furthermore, the approach proposed to determine the buffer sizes is based on the analysis of critical and non-critical chains. Prior to describing the methodology, the notations are given (Table 2). We introduce the metrics that affect the size of the time buffers. Apart from the network complexity measures, we intend to consider the resource stability metrics due to the explicit inclusion of resource usage profiles that make our method different from the traditional buffer sizing analysis.

Table 2. The Notations of Buffer Sizing Method

Symbol	Description
I	Set of chains in the project network
J	Set of project activities
K	Set of renewable resources
T	Set of time slots
r_{jk}	The resource requirement of the j-th activity for k-th resource
R_{kt}	The maximum resource unit available during the planning horizon
PD_j	The number of direct predecessors of j-th activity
SS_j	The number of direct successors of j-th activity
μ_j^2	Expected duration of the j-th activity
σ_j^2	Duration variance of the j-th activity
CC_j	Criticality metric for j-th activity
FF_j	Free float time of j-th activity
ES_j	Earliest possible start time of j-th activity
AC_j	Complexity metric for j-th activity
C_{CC}	Complexity metric of the critical chain
$C_{NCC(i)}$	Complexity metric for i-th noncritical chain
$d_{NCC(i)}$	The dependence metric value for the noncritical chain *i*
$M_{NCC(i)}$	A subset of the activities on the critical chain common with non-critical activities on chain *i*
$\|\|N_{CC(i)}\|\|$	The number of activities on noncritical chain *i*
$D_{NCC(i)}$	Dependency metric for i-th noncritical chain
$M_{NCC(i)}$	The set of activities belongs to the critical chain in common with the activities on i-th noncritical chain.
$Flex_{CC}$	Flexibility metric of critical chain
$Flex_{NCC(i)}$	Flexibility metric of i-th noncritical chain
F_{CC}	Flexibility metric of critical chain
$F_{NCC(i)}$	Flexibility metric of i-th noncritical chain
w_j	Complete weight for j-th activity
δ_j	Normalized weight of j-th activity on the critical chain
RM_j	Robustness metric of j-th activity
rm_{min}	Threshold value of robustness metric
R_j	The stability metric for j-th activity
η	A scale factor of the duration variability

The buffer sizing model consists of two main steps. In the first step, the impacts of the internal uncertainty or potential risk are quantified as regards the characteristics of the project. It is assumed that the inherent characteristics of the project are associated with the project flexibility, schedule robustness, network complexity, and chain dependency metrics. The study attempts to include the above-mentioned structural features of the project to economically determine the size of the time buffers. It should be remarked that the complexity indicators are formulized for the activities as well as critical and noncritical chains. Flexibility indicators are also defined for both the critical and noncritical chains. In order to measure the stability of the buffered schedule generated, the robustness indicators are introduced for both the critical and non-critical chains. In the second step, given the focus on the critical chains, the procedure continues by determining the size of feeding buffers for noncritical chains. External risks and their interdependencies are quantified using a network-based risk interaction analysis, and the results including the degree of risk and criticality of the activities are considered.

3.1 Chain Complexity and Dependency Metrics

In this section, the analysis of the complexity in the project network is discussed. The metrics proposed are related to the internal complexity of the project network. The complexity is defined using an activity-dependent density function and also the effects of the relative weight of activities. The numbers of the precedence relationships indicate that an activity can be a critical component of a project. Thus, more successors and predecessors impose more delays on the network. The activity complexity index (AC) is defined based on an average value of the relative weight of the successor activities.

$$AC_j = \frac{1}{\|PD_j\|}\sum_{j' \in PD_j}\frac{\|SS_{j'}\|}{n} \quad j \in J \tag{1}$$

The complexity of a chain has the largest complexity of its activities. Thus, it is required to define a measure of the complexity for a chain. In the present study, the critical chain complexity (C_{CC}) is calculated as the maximum value for the complexity of activities on the critical chain:

$$C_{CC} = \max_{j \in \{CC\}} \{AC_j\} \tag{2}$$

Likewise, the complexity index of the noncritical chain ($C_{NCC(i)}$) is computed as the maximum complexity of its activities:

$$C_{NCC(i)} = \max_{j \in \{NCC(i)\}} \{AC_j\} \quad i \in I \tag{3}$$

In the next part, we analyze the dependency degree among activities. The dependence factor is just defined for the noncritical chains; the dependence factor calculates the percentage of the activities on the critical chain that belongs to the noncritical chain. More precisely, it is defined as the percentage of the overlap between the activities belonging to the noncritical chain and the critical chain. The higher the value of dependency degree is, the more it will be indicative of the interdependence between the related noncritical chain and the critical chain. According to the definition, the dependence degree value is between zero and one ($0 \le d_{NCC(i)} \le 1$).

$$d_{NCC(i)} = \frac{\|M_{NCC(i)}\|}{\|NCC(i)\|} \quad i \in I \tag{4}$$

To formulize the effects of the dependency degree on the buffer sizes, threshold values are required to determine the significant degree of the dependency index on the critical chain (δ_1 and δ_2). If the dependency degree computed is larger than the threshold value (δ_2), the buffer allocated to the critical chain will increase; otherwise, it may be constant or may decrease the buffer sizes. In conclusion, the normalized dependency degree designated by the symbol $D_{NCC(i)}$ is presented in Eq. (5):

$$D_{NCC(i)} = \begin{cases} 1-\Delta & 0 \le d_{NCC(i)} < \delta_1 \\ 1 & \delta_1 \le d_{NCC(i)} \le \delta_2 \\ 1+\Delta & \delta_2 \le d_{NCC(i)} \le 1 \end{cases} \tag{5}$$

where the amount of increase or decrease of the buffer size equals to Δ.

3.2 Flexibility Metric

Flexibility is a relevant quota in the project management discipline. A schedule is called flexible if it resists delays and can be repaired at the minimal cost. Previous studies define the flexibility of activities as the total Flotation Time (TF). The present study proposes the free float (FF_j) factor of activities as a measure of schedule flexibility. The free float is the amount of the time that an activity can be delayed without postponing the early start of its successor activities. In this case, the successors can start at the earliest possible time, (ES_j), and the free float is computed as follows:

$$FF_j = ES_{j' \in SS_j} - EF_j \quad j \in J \tag{6}$$

After introducing the notation above, we calculate the critical chain flexibility as the minimum free float on the critical chain activities belonging to them. The higher the flexibility of the critical chain is, the fewer time buffers will be required

$$Flex_{CC} = \min_{j \in \{CC\}} \{FF_j\} \quad j \in J \tag{7}$$

The concept of safety float is relevant for the noncritical chains, if the activities do not inevitably delay the project makespan. Thus, the flexibility metric of non-critical chains is defined by the safety float (SF_j) of activities belonging to them. The safety float refers to the maximum time that an activity is allowed to be postponed without suspending the makespan. Likewise, the noncritical chain flexibility is calculated as the minimum safety flotation of the activities on the i^{th} non-critical chain.

$$Flex_{NCC(i)} = \min_{j \in \{NCC(i)\}} \{SF_j\} \quad i \in I \tag{8}$$

Given the equations above, threshold values are required to analyze the effects of the chain flexibility on the sizes of the time buffers. Consequently, the rate of increasing or decreasing the buffer time depends on the amount of the normalized flexibility. In this study, the flexibility threshold values are different for critical and noncritical chains. The threshold values of the critical chain flexibility are denoted by a and b. The threshold values define the minimum free float on the critical path activities. The range of insensitivity of the flexibility of the critical chain is defined within the range [a, b].Thus, in this range, the amount of flexibility has no impact on the size of the buffer time. If the critical chain flexibility has a smaller amount than a threshold value a, then the sensitivity threshold value f_A is an indicator of the flexibility in the final buffer sizing model. Also, if the critical chain flexibility is larger than the threshold value b, then the ratio f_B is an indicator of the flexibility. According to the above definition, the amount of f_A is greater than 1 and f_B is lower than 1.

$$F_{CC} = \begin{cases} f_A & Flex_{CC} < a \\ 1 & a \le Flex_{CC} \le b \\ f_B & Flex_{CC} > b \end{cases} \tag{9}$$

Similarly, threshold values for the noncritical chain flexibility equal a_i, and b_i. Thus, the flexibility of a non-critical chain is calculated as:

$$F_{NCC(i)} = \begin{cases} f_A(i) & Flex_{NCC(i)} < a_i \\ 1 & a_i \le Flex_{NCC(i)} \le b_i \\ f_B(i) & Flex_{NCC(i)} > b_i \end{cases} \tag{10}$$

3.3 Robustness Measure

The degree of the start time stability of the activities determines the degree of the schedule robustness against the changes and delays. As regards the existing method, the Criticality Index (CI) was defined as the ratio of the average daily amount of the resource requirement to the daily amount of the resources available (Moder and Davis, 1983). The larger the critical measure of the resources is, the higher the probability of delays in the project will be. In this study, the degree of robustness is calculated on the basis of the integrated statistical measures and resource tightness index.

The robustness metric is defined according to the coefficient of variation (CV). It measures the schedule reliability, being indicative of the level of uncertainty in the model (Herroelen and Leus, 2001). Formally, CV is the ratio of the standard deviation to the average value of the activity duration:

$$CV_j = \frac{\sigma_j}{\mu_j} \tag{11}$$

The small value of CV allows for a minor degree of variability in the project planning, so the buffer sizes are relatively small in this case. In the present study, the concept of resource tightness and the coefficient of variation are combined. Thus, a new robustness metric (RM_j) for j$^{\text{th}}$ activity is defined. For the activities belonging to the critical chain ($j \in \{CC\}$), the robustness metric is calculated as a normalized ratio of the weighted coefficient of variation of critical activities:

$$RM_j = \frac{\delta_j CV_j}{\sum_{j' \in \{CC\}} \delta_{j'} CV_{j'}} \qquad j \in \{CC\} \tag{12}$$

In the equation above, a total weight (w_j) for j$^{\text{th}}$ activity has been defined. This total weight indicates that, for various resources required for an activity, the maximum ratio of resource requirements is divided into the maximum level of the resource units available over time ($t \in T$). The higher the weight is to be expected a source of disruption, so it is more essential to be condensed. The negative effects must also be taken into account.

$$w_j = \max_{k \in K} \left\{ \frac{r_{jk}}{\min\limits_{t \in T} \{R_{kt}\}} \right\} \qquad j \in \{CC\} \tag{13}$$

Additionally, it is required to define the normalized weight for the activity that belongs to the critical chain (δ_j).The higher the normalized weight is, the more it will be indicative of the tendencies to seize the maximum level of the resources and accordingly lead to more delay. In conclusion, the normalized weight of critical activities is defined as:

$$\delta_j = \frac{w_j}{\sum_{j' \in \{CC\}} w_{j'}} \qquad j \in \{CC\} \tag{14}$$

Likewise, for the activities belonging to the i$^{\text{th}}$ noncritical chain, the robustness metric is computed as a normalized ratio of the weighted coefficient of the variations:

$$RM_j = \frac{\delta_j CV_j}{\sum_{j' \in \{NCC(i)\}} \delta_{j'} CV_{j'}} \qquad j \in \{NCC(i)\} \tag{15}$$

The less the value of the robustness metric is, it will be indicative of fewer buffer times. Consequently, it is required to define the threshold values in order to quantify the effects of the robustness metric on the size of the time buffers. The threshold values have significant effects on the quality of the buffered schedule. Therefore, the researchers of this paper define a minimum value of robustness metric that triggers the increase of the buffer size. This threshold value is denoted by rm_{min}, and it indicates that the robustness metric is higher than the threshold value ($RM_j > rm_{min}$). In such a condition, the value robustness for each activity (R_j) increases by $\Delta = 5\%$.

$$R_j = \begin{cases} 1 + \Delta & RM_j > rm_{min} \\ 1 & RM_j \le rm_{min} \end{cases} \tag{16}$$

3.4 Risk Analysis of Buffer Sizing Model

Risk and uncertainty are two intertwined concepts in project management. According to the Project Management Body of Knowledge (PMBOK) standard, a risk is concerned with an uncertain event or condition that specifies a positive or negative effect on at least one of the goals of the project dimensions such as time, cost, scope and quality (Jaafari, 2001). The definition of risk is not clear enough and its overlap with uncertainty is quite ambiguous (Perminova and Wikström, 2008). The effects of risks on the project completion time are different (Herroelen, 2014). In the first case, it has a relative or fixed-term influence on the duration of activities. In the second case, the risk is associated with the delay or suspension of the execution of activities. In the third case, the risk is initiated as result of a halt of the execution of activities due to the unavailability of the resources. In the present study, we analyze the effects of the risk on other sources of the risk in order to quantify the way that risk factors interact with each other and propagated in the whole project network.

This research follows the main steps of the traditional risk assessment models comprised of identifying, quantifying and assessing the degree of uncertainty in the project network. However, the classic risk quantification process is not suitable for managing all real-world project planning problems. This study adopts a network-based risk assessment approach originally proposed by Marle and Vidal (2008) for analyzing the effects of risk events on the buffer sizes. The required notation are provided in Table 3. In this risk assessment method, after identifying potential

Table 3. The Notations of the Risk Assessment Model

Symbol	Description
RSM_{ij}	= 1 if there is a cause and effect relationship between the risk factors of R_j and R_i and it is equal to 0 otherwise.
RNM_{ij}	Cause-effect interaction from R_j to R_i in the risk numerical matrix
$C(R_i)$	The criticality of risks R_i
$G(R_i)$	The initial cruelty of the risk event assessed for the risk R_j
$P_{Ri}(R_j)$	The probability of risk R_j as the consequence of $P(R_i)$
CR	The final indicator of the impact of external risks on project performance
CR_{min}	Threshold value of the criticality metric
$\overline{CR}$	Averaged value of the criticality metric

risk events, the next step is to determine the occurrence and impacts. Then the dependence degree and the interactions among the risk factors must be determined. The interactions among risk factors are formally expressed by the cause-effect relationship between each pair of risk factors.

In this step, we adopt a Risk Structure Matrix (RSM). The risk assessment methodology is continued by incorporating the probability and impacts of the risk events into the RSM. The structure of the risk analysis is conducted through a zero-one matrix where the value of 1 specifies the link between risks R_i and R_j. A key question is about the extent of the interactions among risk events.

Two types of probabilities are calculated for project risks. The first one is the occurrence probability of a risk to be initiated by another risk factor inside the network, called spontaneous probability. Another probability is the one caused by external events being called transition probability. These two probabilities are used in RSM. The transformed matrix is called the Risk Numerical Matrix (RNM) which evaluates the risk interactions. In this approach, a risk event may be initiated several times during the project execution phase, due to the different sources of the risk or the same causes of the delay. Therefore, the risk assessment procedure is followed by an analysis of the risk propagation rate through the project network. N denotes the risk factors which are identified through the Risk Breakdown Structure (RBS). The vector s signifies the vector of initial probabilities of the risk factors. Furthermore, N-order square numerical matrix A represents the matrix of transition probabilities. The vector $P(R)$ denotes the updated risk probabilities obtained from the risk propagation analysis (Fang and Marle, 2012). The propagation analysis is performed for m stages. Thus, the transmitted vector of risk probabilities equals $\mathrm{A}^{\mathrm{m}}.\mathrm{s}$. The risk probability vector is reevaluated and the final value is calculated using the following equation:

$$P(R) = s+\sum_{i=1}^{m} = A^{i}.s = (I+\sum_{i=1}^{m}A^{i}).s = (\sum_{i=0}^{m}A^{i}).s = (I-A)^{-1}.s \tag{17}$$

In order to quantify the effects of the risk assessment on the buffer sizing model, we need to measure the criticality of the risk factors which is the product of probability and impact of risks. As suggested by Fang and Marle (2012), the criticality metric is computed by incorporating all probabilities and potential consequences. In conclusion, the updated risk criticality metric is computed utilizing the following equation:

$$C(R_i) = \sum_{j=1}^{n} G(R_j).P_{Ri}(R_j) = G^{T}.(I-A)^{-1}.(I^{i}.P(R_i)) \tag{18}$$

The new value of the criticality index may alter the risk prioritization results. If such a condition is met, then it will have a direct effect on the sizes of the time buffers. CR denotes the measure of the change in the criticality metric after the risk propagation analysis. Therefore, the initial risk probabilities and critical values are observed to find how they are evolved during the propagation analysis. If the rate of criticality changes is significant, then the project will face more uncertainties, and the buffer sizes will increase. To evaluate the impact of the initial and final values for the criticality metric on the buffer sizes, the criticality rate of all project activities is averaged. Therefore, the average criticality is a basis for modifying buffer sizes. The threshold value of the criticality metric is denoted by CR_{min}. If the averaged value of the criticality metric ($\overline{CR}$) is higher than the threshold value, then the buffer size will increase by $\Omega = 5\%$:

$$CR = \begin{cases} 1+\Omega & \overline{CR} > CR_{min} \\ 1-\Omega & \overline{CR} \le CR_{min} \end{cases} \tag{19}$$

CI_{CC} and F_{CC} represent the final adjusted complexity and flexibility metrics, respectively. After explanation given above, the project and feeding buffers can be calculated using the following equations:

$$PB = \eta \times CR \times CI_{CC} \times F_{CC} \times \sqrt{\sum_{j \in \{CC\}} R_j.\sigma_j^2} \tag{20}$$

$$\begin{aligned} FB_i = {} & \eta \times CR \times CI_{NCC(i)} \times D_{NCC(i)} \times F_{NCC(i)} \\ & \times \sqrt{\sum_{j \in \{NCC(i)\}} R_j.\sigma_j^2} \qquad i \in I \end{aligned} \tag{21}$$

Complexity and flexibility metrics are multiplied by the square root of the sum of the weighted variance of project activities. Accordingly, the size of the feeding buffer is calculated by multiplying the weighted sum of the square root of the variances and the value of criticality, complexity, dependency, flexibility metrics and a scale parameter (η) for the time variability. In the next section, the researchers of this study provide a benchmark analysis and a real-work case study to validate the buffer sizing model proposed.

4. Case Studies

This section provides a benchmark analysis in order of verifying the applicability of the buffer sizing method proposed. The benchmark analysis of the critical chain project management is conducted through a real case study adopted from a study carried out by Ma *et al.* (2014). The real case is concerned with the transport infrastructure construction projects in China. The scheduled project makespan, general information of the tasks and resources are given in Table 4. The project network and the precedence relationships are illustrated in Fig. 1. The critical chain of the project is A-B-C-D-E-H-I-J-L-N-T-U. The length of the critical chain equals 350 days. The project consists of four

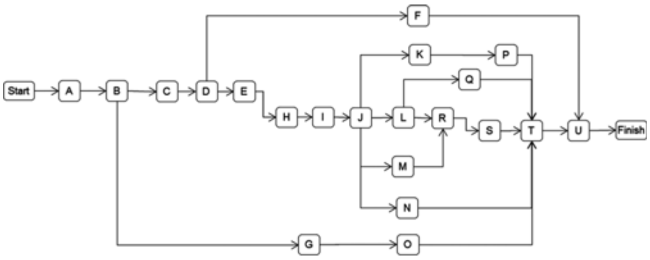

Fig. 1. The Project Network Adopted for the Benchmark Analysis

Table 4. The Information of the Benchmark Case

Activity name	Expected duration	Resource requirement			Standard deviation of activity duration
		R1	R2	R3	
A	5	38	18	5	0.7
	7	35	16	3	
	8	32	14	2	
B	50	37	15	6	3.36
	56	35	12	4	
	65	32	8	3	
C	35	28	15	4	4.32
	40	24	13	2	
	45	22	10	1	
D	8	25	18	8	0.92
	12	20	16	5	
	16	18	14	3	
E	30	25	12	23	5.58
	45	20	8	20	
	50	15	5	18	
F	170	13	13	12	15.3
	180	9	10	9	
	190	7	8	7	
G	145	14	15	10	9.4
	150	10	12	8	
	156	8	10	8	
H	38	30	11	21	5.13
	45	27	11	21	
	50	25	10	20	
I	35	13	16	9	6.17
	45	10	16	8	
	55	9	16	8	
J	18	12	17	9	1.52
	20	10	16	8	
	23	10	16	8	
K	10	3	6	3	1.82
	15	1	4	3	
	20	1	3	3	
L	15	9	10	3	0.84
	20	7	8	3	
	25	7	6	3	
M	8	11	4	3	1.17
	10	2	2	3	
	13	5	2	3	
N	45	10	6	3	3.7
	48	7	6	3	
	50	5	5	3	
O	80	18	18	17	8.19
	90	16	17	17	
	95	14	14	17	
P	35	8	8	3	4.16
	38	5	6	3	
	42	3	5	3	
Q	20	5	6	3	2.65
	25	3	5	3	
	30	1	4	3	
R	10	14	5	0	1.3
	12	12	2	0	
	15	9	2	0	
S	20	6	4	0	5.45
	25	4	2	0	
	30	2	2	0	
T	5	16	4	0	1.28
	7	12	3	0	
	10	10	3	0	
U	3	15	0	0	1.02
	5	12	0	0	
	8	9	0	0	

Table 4. (continued)

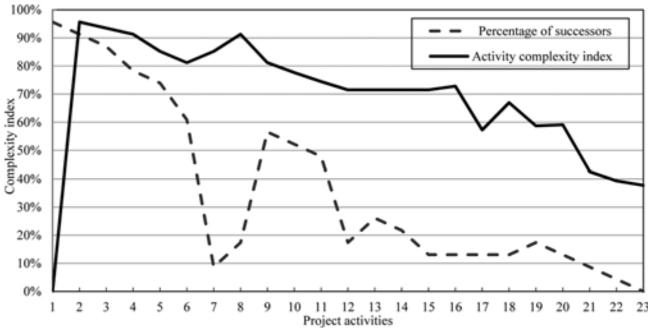

Fig. 2. The Complexity Metric of the Project Activities in Benchmark Case

noncritical chains comprised of F, K-P, R-S (Q-M) and G-O. The project buffer must be inserted after activity U. Furthermore, the feeding buffers are allocated to the activities of F, P, S and O.

4.1 Computational Results of the Benchmark Analysis

In this section, the computational results of the benchmark analysis are provided. The activity complexity and criticality metrics are calculated for each activity in the case study. As it can be seen in Fig. 2, the network complexity and criticality values have a similar pattern. The diagram is indicative of a comparative decrease in the complexity of the last activities of the project.

The benchmark method is being called "improved CCPM" (ICC/PM) takes into consideration the External Uncertainty (EU) in the buffer sizing process. The approach was based on the extended RSEM method. After the critical and noncritical chains are identified, the project and feeding buffers should be inserted in the suitable positions. The following equations are adopted from the ICC/PM method that calculates the project and feeding buffer sizes:

$$PB = EU \times RP \times AC_{CC} \times \sqrt{\sum_{j \in \{CC\}} (1+RT_j).AF_j.\sigma_j^2} \tag{22}$$

$$FB_i = EU \times RP \times AC_{NCC(i)} \times \sqrt{\sum_{NCC(i)} (1+RT_j).AF_j.\sigma_j^2} \tag{23}$$

Accordingly, the buffer sizes are calculated as follow:

Table 5. Computational Results of Buffer Sizing Models on Benchmark Analysis

Buffer sizing approach	Project buffer	Feeding buffer 1	Feeding buffer 2	Feeding buffer 3	Feeding buffer 4	Total buffer (days)
ICC/PM	19	0	2	9	10	40
Multi-attribute buffer sizing method	17.4	0.8	3.8	4	8	34
Change percentage	-8.42%	70.00%	90.00%	-55.56%	-20.00%	-15.00%

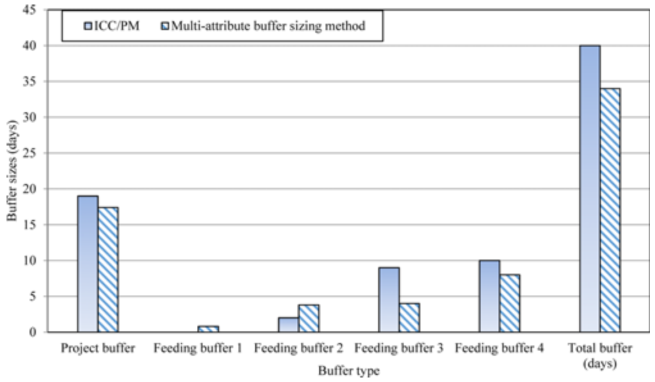

Fig. 3. The Comparative Results of the Buffer Sizing Model

Table 6. Results of Buffer Sizing Models on The Benchmark Case

Buffer sizing approach	Probability of on-time project completion time	Average delay (days)	Variance of delay (days)	Total buffer
RSEM	92.10%	18.6	6.8	36
C&PM	99.50%	5.4	3.2	175
ICC/PM	96.20%	15.2	5.8	40
Multi-attribute buffer sizing method	97.30%	13.5	5.3	34

$$PB = 19, FB_F = 0, FB_P = 2, FB_S = 9, FB_O = 10 \tag{24}$$

Researchers of this study summarized the results of the buffer sizing method in Table 5. The table provides the amount of buffer sizes generated from ICC/PM and our method in the benchmark case study. According to the results obtained from the multi-attribute buffer sizing method, the total size of the time buffers has been reduced by almost15% (Fig. 3). Indeed, the total time buffer allocated has been reduced by 6 days. The results indicate that the buffer times have been distributed more appropriately. This result indicates that the improved stability of the generated buffered schedule can be achieved using the multi-attribute buffer sizing method. As it can be seen, the percentages of the changes in the size of the feeding time buffers on noncritical chains 1 and 2 are significant, with an approximate increase of 70% and 90%, respectively. The project buffer size has been reduced by -8.42% as against the benchmark buffer sizing method.

The buffer sizing method proposed is validated through the Monte-Carlo simulation method. It is assumed that the probability distribution function of each project activity follows a normal distribution with a known mean and variance. Therefore, the cumulative distribution of the completion time of the project is calculated using the Monte-Carlo simulation technique. The total number of simulation replication is n = 1000, in order to achieve solutions with the least variance.

The results of the schedule performance analysis are given in Table 6. The robust buffer sizing method proposed is compared to the most applicable buffer sizing methods such as C&PM, RSEM and ICC/PM. The results demonstrate that C&PM method generates the most stable project plan (99.5% of on-time completion). However, the project buffer size is very high (175 days), so it cannot be economically acceptable. The C&P method is not economical because it adopts a linear way to determine the size of the buffers. Thus, buffer size increases linearly with the duration of the critical chain, which frequently results in unreasonably long makespan and leads to extra cost. It can be concluded that C&PM is a very simple buffer sizing approach which may result in significant time buffers not applied in practice. The multi-attribute buffer sizing method could generate a buffered schedule with a higher degree of robustness as against the traditional RSEM and ICC/PM. The results of buffer sizing models on the benchmark case include the average and variance of delay. As can be seen, the proposed multi-attribute buffer sizing method outperforms the RSEM and ICC/PM. In fact, a more effective buffer sizing method incorporates the complexity, flexibility, interdependency, robustness, and criticality metrics to adjust the feeding and project buffer sizes.

In order to make a fair comparison, the cumulative probability distribution plots are illustrated for different approaches. A cumulative probability distribution function is usually drawn as an S-Curve diagram illustrating the accumulative probability of the completion time of the project. This chart conveys important information to decision makers and project managers as to the level of reliability of the project plan. The results of the cumulative probability distribution specify that the buffered schedule obtained from the multi-attribute buffer sizing model

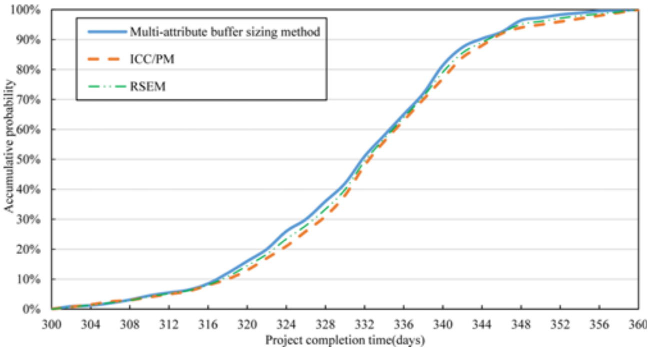

Fig. 4. Cumulative Probability Plots

Table 7. Results of Effects of Coefficient of Variation on Buffer Size

Coefficient of variation (CV)	C&P Method	RSEM	ICC/PM	Proposed multi-attribute buffer sizing method
0.5	175	18	20	17
1	175	36	40	34
1.5	175	54	60	51
2	175	72	80	68
2.5	175	90	100	85
3	175	108	120	102
3.5	175	126	140	119
4	175	144	160	136
4.5	175	162	180	153
5	175	180	200	170
5.5	175	198	220	187
6	175	216	240	204
6.5	175	234	260	221
7	175	252	280	238
7.5	175	270	300	255
8	175	288	320	272
8.5	175	306	340	289
9	175	324	360	306
9.5	175	342	380	323
10	175	360	400	340

proposed is more likely to be completed on time, and that it will not delay the project due date (Fig. 4). Consequently, the method proposed outperforms the existing buffer sizing model in terms of schedule robustness.

A simulation-based experiment is conducted to study the impact of external risk factors on the size of the buffers. The influence of the external risk factors is associated with an increase in the variability of the system. Incidentally, different values of the standard deviation of the activity duration (σ) are measured. Results of effects of the coefficient of variation on the buffer size are given in Table 7. As it is noticeable, the buffer sizes generated from the C&P method will not change by an increase or decrease in the standard deviation of activities; hence, it indicates that this method is not applicable to the real-world case studies. As illustrated in Fig. 5, the buffer size changes are rather different for the multi-attribute buffer sizing method, RSEM and ICC/PM. Upon the increased variance of the activity, the graph shows that the buffer size grows linearly by a factor of increasing the standard deviation. The multi-attribute buffer sizing model has the slowest rate of change against other buffer sizing methods. It is worth mentioning that the intersection points illustrated in Fig. 5 are considered as the basis for a breakeven analysis.

Based on the results obtained, as the standard deviation of the activity duration increases, the influence of external risks on the buffer size becomes different for buffer sizing models. For example, a very high CV is very rare in practice, so the obtained buffer size of the existing methods (i.e., C&PM and RSEM) has a high rate of risk and uncertainty for real-world implementation.

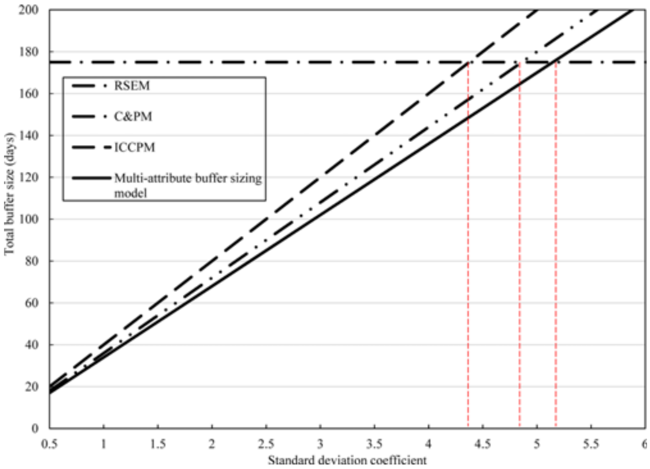

Fig. 5. The Variation of the Buffer Sizes Against Coefficient of Variation (CV)

In conclusion, the buffered schedule generated using the multi-attribute buffer sizing method proposed is more likely to be completed on time. Moreover, the buffered schedule generated has a more economical buffer size, and the schedule robustness has increased. The mean and variance of the delays of the project completion time for the schedule generated by the method presented were reduced as against the existing buffer sizing methods; this signifies the effectiveness of the present multi-attribute buffer allocation methodology.

4.2 Sensitivity Analysis

This section provides the sensitivity analysis of the buffer calculation to the uncertainties (or errors) of intermediate indicators, including risk and activity network-based metrics. The fact is that indicators which are multiplied may potentially amplify an initial mistake. In order to validate the buffer sizing model, the researchers of this paper tested the buffer sizes against different levels of uncertainties and threshold values. The results of the sensitivity analysis are provided in Table 8. The outcomes indicate the low sensitivity of the time buffers generated against different values of the model parameters.

4.3 A Real World Application of Engineering Project

This section examines the efficiency of the methodology proposed to improve the project robustness. Firstly, a brief description of a real-world case will be explained. Then, the data

Table 8. Sensitivity Analysis of the Multi-attribute Buffer Sizing Method Against Model Parameters

CV	Δ	rm_{min}	CR_{min}	PB
0	1%	0.1	0.2	16.5
0.5	5%	0.2	0.4	18.9
1	10%	0.5	0.5	23.2
1.5	1%	0.6	0.2	27.1
2	5%	0.8	0.4	32.5
2.5	10%	0.9	0.5	38.3

Table 9. Activity Durations and Precedence Relationships Among Tasks

Activity code	Activity duration (days)	Precedence relationship
A1	50	-
A2	100	1SS+30 days
A3	80	2FF-20 days
A4	160	2FS
A5	60	3SS+20 days,4FS
A6	60	5FS
A7	80	11,5FS+10 days
A8	150	3FF+50 days,11FS
A9	90	8FS,7FS
A10	50	6SS+100 days,12FS,9FS

Table 10. Probability Distributions for Project Activities

Maximum duration (c)	Most-likely duration (b)	Minimum duration (a)	Probability distribution	Activity code
85	50	35	Triangular	A1
140	100	60	Triangular	A2
100	-	55	Uniform	A3
210	160	120	Triangular	A4
90	60	45	Triangular	A5
90	-	45	Uniform	A6
110	80	60	Triangular	A7
180	150	120	Triangular	A8
110	90	70	Triangular	A9
85	50	30	Triangular	A10

Table 11. The Information of the Activities

Activity code	duration Approximated	Total Float (days)	Free Float (days)	Maximum availability of resources
A1	50	0	0	3 , 4
A2	100	0	0	4
A3	80	240	120	3
A4	160	0	0	13
A5	60	0	0	5 , 4
A6	60	80	80	8
A7	80	0	0	7 , 2
A8	150	160	160	4
A9	90	0	0	14
A10	50	0	0	3

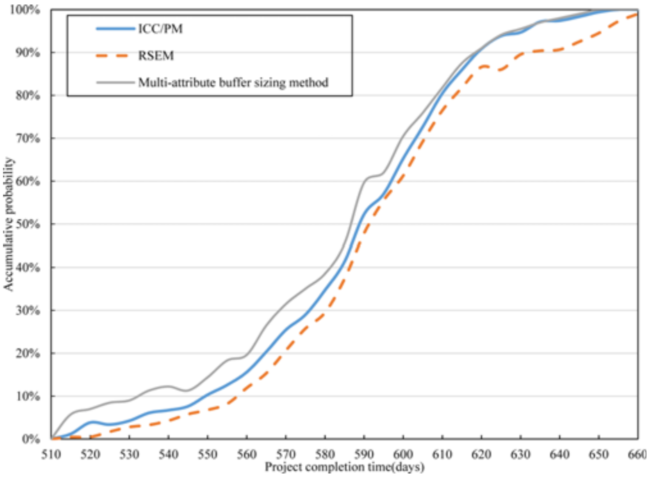

Fig. 6. The Probability Plot of the Buffer Sizing Models

collection, simulation results and validation tests are to be discussed. The case study consists of an engineering phase of the gas field construction and an extraction project in Iran. Table 9 illustrates the activity durations and the precedence relationships among the tasks. Probability distributions for project activities and parameters associated are given in Table 10. The table provides durations for the best-case, worst-case and most likely scenarios. Other relevant important information of the project activities is given in Table 11. As noticed in this table, a project manager calculates the contingency buffers for changes, errors and delays, according to the past experience and engineering judgment methods.

If all activities are carried out with their minimum durations, the project will be completed in 585 days. Based on the simulation experiments, the project was simulated for n = 1000 replications and the average makespan was 605 days. The S-curve of the project duration distribution is illustrated in Fig. 6. As to the outcomes, the project completes before 646 days at the probability rate of 90%. This indicates a delay amounting up to 62 days with respect to the initial estimation of the project makespan.

5. Conclusions

In this study, an innovative buffer sizing method was proposed based on flexibility, complexity, robustness and dependency metrics to determine the size of the project and feeding buffers under the risk condition. The proposed buffer sizing approach utilized a network-based risk interaction analysis for quantifying the impacts on the size of the time buffers. The efficiency of the buffer sizing model was examined through simulation experiments. The comparative results of the novel buffer sizing method gave evidence for the efficiency of the robust multi-attribute buffer sizing method presented in the real world project. Finally, some of the strengths and the limitations of the buffer sizing approach proposed were discussed. It was verified that the size of the time buffers determined by the method proposed is more reasonable and economical, demonstrating its capability to manage project planning under uncertainties.

The ventures for the proposed multi-attribute CC/PM approach to be accepted by the construction industry are encouraging as a result of a number of motives. First, the risk mitigation approach is based on further realistic expectations than existing buffer sizing methods such as the flexibility of the framework to include different user criteria. Second, the proposed buffer sizing model is acquainted with different resource usages and the risk preference, which are better descriptions of managerial observes and allows for more flexible adjustments of project schedules when disruptions happen. Third, the proposed buffer sizing model was extended on the basis of CC/PM which is a well-known approach in project management discipline. Thus, the time and effort required to train the users and risk managers are really reduced by the model application. The presented buffer sizing model provides justifiable and operable instructions on buffer sizing method that makes it easy to be implemented in construction industry.

In future researches, the present buffer sizing approach can be extended by incorporating a multi-objective framework for the analysis. Also, the method of designing the baseline project schedule has a significant effect on the performance of the CC/PM approach. Thus, further researches should be directed towards using different scheduling policies e.g. priority list scheduling. Furthermore, the resource leveling algorithms can be integrated with the buffer sizing model to enhance the quality of the solutions generated.

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