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Determining a fuzzy model of time buffer size in critical chain project management

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ABSTRACT

Elaborating and applying a new model for estimating the time buffer size of a project programme, which shall guarantee a 90 % probability of timely project execution. The research included source text analysis to provide information on a research gap and the identification of the research problem. The research problem was identified: the time buffer size in a critical path programme does not guarantee a 90 % probability of timely project execution. A new model was then elaborated to estimate the buffer size; it was applied in a technical production preparation project. An additional comparative analysis was performed using the following methods to verify the model more accurately: half of the time total of a path, the sum of squares (SSQ), and the root square error method (RSEM). The application of the fuzzy model to estimate the buffer size in a critical chain programme offers can shorten the total planned project duration. It has a higher probability of timely project execution than other methods for estimating the buffer size. It guarantees a 90 % probability of timely project execution, keeping aggressive task times, which eliminates unwanted situations such as student syndrome, Parkinson's law, overestimating task duration, and multitasking. Project programming is an inherent part of the project planning stage in project management. Recently, project management has been increasingly developing, which has been confirmed by the article's source literature analysis. The analysis revealed a research gap in models estimating project buffer size, which might guarantee a 90 % probability of timely project execution. Thus, a fuzzy model for estimating time buffer size in a critical chain was developed, constituting added value to the science of management and quality of production engineering (currently, mechanical engineering). The fuzzy model for estimating time buffer size was applied in one Polish enterprise in a project for a new product's technical production preparation. The fuzzy model for estimating time buffer size permits the shortening of the duration of tasks to aggressive times, guaranteeing a 90 % probability of project timely execution. The elaborated model for estimating time buffer size may be applied further in practice in projects programmed using the critical chain method.

KEY WORDS

project management, project scheduling, critical chain project management, time buffer, buffer size, fuzzy sets

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Introduction

Project scheduling is a standard activity of every business unit that applies the project approach in its activity management. Research of the past quarter of the century shows that success depends on many factors. In the 1960s and 1980s, project success was measured by cost, time, and scope, also known as the iron triangle of project management (Atkinson, 1999). Over time, new project success factors have emerged, e.g., the satisfaction of key stakeholders, including the project team and sponsors (Jugdev

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& Müller, 2005; Shenhar et al., 2001; Serrador & Turner, 2014; Turner & Zolina, 2012; Young & Poon, 2013), competences of the project team, achieving strategic goals, appropriate communication (Cserháti & Szabó, 2014; PMI, 2013), using methodologies, methods, and techniques supporting project management, risk management, optimisation end clearly defined business goal (Hass, 2010; Müller & Turner, 2007, The Standish Group, 2013; Sebestyen, 2017; Martens et al., 2018). Critical success factors (CSF) vary depending on the industry in which projects are being implemented (Spalek, 2014; Urbański et al., 2019). However, regardless of the industry, there are common factors that can be identified:

- defining appropriate project aims, resources, and parameters,
- supporting and engaging management staff,
- maintaining project stakeholder relations and informing them of progress in project execution,
- ensuring competencies of managers and project team members,
- establishing project schedule and programme well; properly distributing tasks and duties within a project,
- regularly monitoring and inspecting project risks,
- solving the most important issues at the highest management level,
- optimising the project, i.e., dividing the project into smaller projects,
- using appropriate methodology, project management methodologies or techniques,
- clearly identifying the project aim.

As project success is influenced by the application of an appropriate methodology, an attempt has been made to use an innovative critical chain project management approach, CCPM, developed by Goldratt for the technical project programming for developing a new product's production. The research focused on a method for determining the buffer size of project time.

Critical chain project management constitutes a novel method that reduces the duration of individual tasks, decreases the project execution cost and achieves the determined goal. The method's author assumes that a project manager should go through the following stages (Goldratt, 1997; Leach, 2014) when scheduling a project:

- determining the project's scope, meeting a specified cost and the shortest possible time,
- identifying the critical chain,
- limiting task duration within the critical chain,
- introducing buffers protecting the critical chain,
- determining buffer size,
- monitoring project execution and taking corrective measures.

The project manager estimates the duration of tasks and assumes a safety margin to obtain a guarantee for timely project execution. Goldratt claims that the CCPM method is necessary to reduce the time to aggressive estimations (t0.5), which gives about 50 % certainty of timely task execution, and to introduce time buffers. According to Leach (2005), a buffer is "a process surplus, time span or budget assigned, applied for protecting the flow planned, delivery time or estimating cost in a production process or a project". Two kinds of time buffers have been distinguished in the critical chain concept: project buffer (PB) and feeding buffer (FB) (Goldratt, 1997; Izmailov et al., 2016; Leach, 1999, 2014; Raz et al., 2003). A project buffer placed at the end of the critical chain to protect the project scheduling removes the student syndrome and secures timely project execution. The feeding buffer connects the noncritical path with the critical chain, protecting the critical chain from a delay on the noncritical path, which can delay project execution.

The project manager uses the CCPM method for project scheduling to determine the size of time buffers. Time buffer size in project scheduling has been frequently targeted by research over the recent years. The research detailed the following methods: a 50 % rule, the square root of the sum of squared differences for estimated time deviation, and the root square error method. Most of these methods outlined in the existing literature do not consider the significant critical chain method assumption, in which project scheduling, after accounting for time limiting and time buffers, must have at least a 90 % probability for timely project execution. Therefore, a research gap exists in the discipline of management and quality sciences, and production engineering. The article's authors attempted to solve the research problem: the size of the time buffers in the critical chain schedule does not provide a 90 % probability of project completion on time. The following research questions will be analysed to solve the research problem:

- What methods estimating the time buffer size have been described in the literature?
- Do the methods described in the source literature guarantee a 90 % probability of timely project execution?
- Can fuzzy numbers be used to determine the time buffer size? Why are they worth being applied?

- How can a 90 % probability of timely project execution be guaranteed?
- Will elaborating a fuzzy model for determining the time buffer size guarantee a 90 % probability of timely project execution?

Answers to the first two research questions were obtained after analysing the literature described in the Literature Review. Answers to the third and fourth research questions are presented in Research Methods, which describes the fuzzy model for estimating the time buffer size in a critical chain programme. The answer to the fifth research question is presented in Research Results and Discussion, which include a case of sample application of a fuzzy model in a project programme, including a new product's technical production preparation and a comparative analysis using other methods for estimating the time buffer size.

1. Literature review

During recent decades, the project planning approach under conditions of uncertainty has become increasingly more common, which gave rise to the search for new methods for the management of programme variability and instability in a research environment. One such method is widely analysed in the literature and includes a critical chain based on Goldratt's theory of constraints. If properly applied, it may reveal flexibility and robustness in project scheduling.

Initially, a review of literature trends in Scopus and Web of Science databases was performed, which showed that the term "critical chain" is growing more popular every year. Figs. 1 and 2 show the scheme created based on a graph generated in VOSviewer regarding the co-occurrence of the term "critical chain" with other terms. After optimisation, five clusters were obtained.

In the examined source query, with "minimum number of occurrences of a keyword" = 5, out of the 1291 keywords, 63 met the threshold. For each of the 63 keywords, the total strength of co-occurrence links with other keywords was calculated. The keywords with the greatest total link strength were selected.

Cluster 1, "Project management", created in VOSviewer, contains concepts related to the critical path method, critical chain project management,

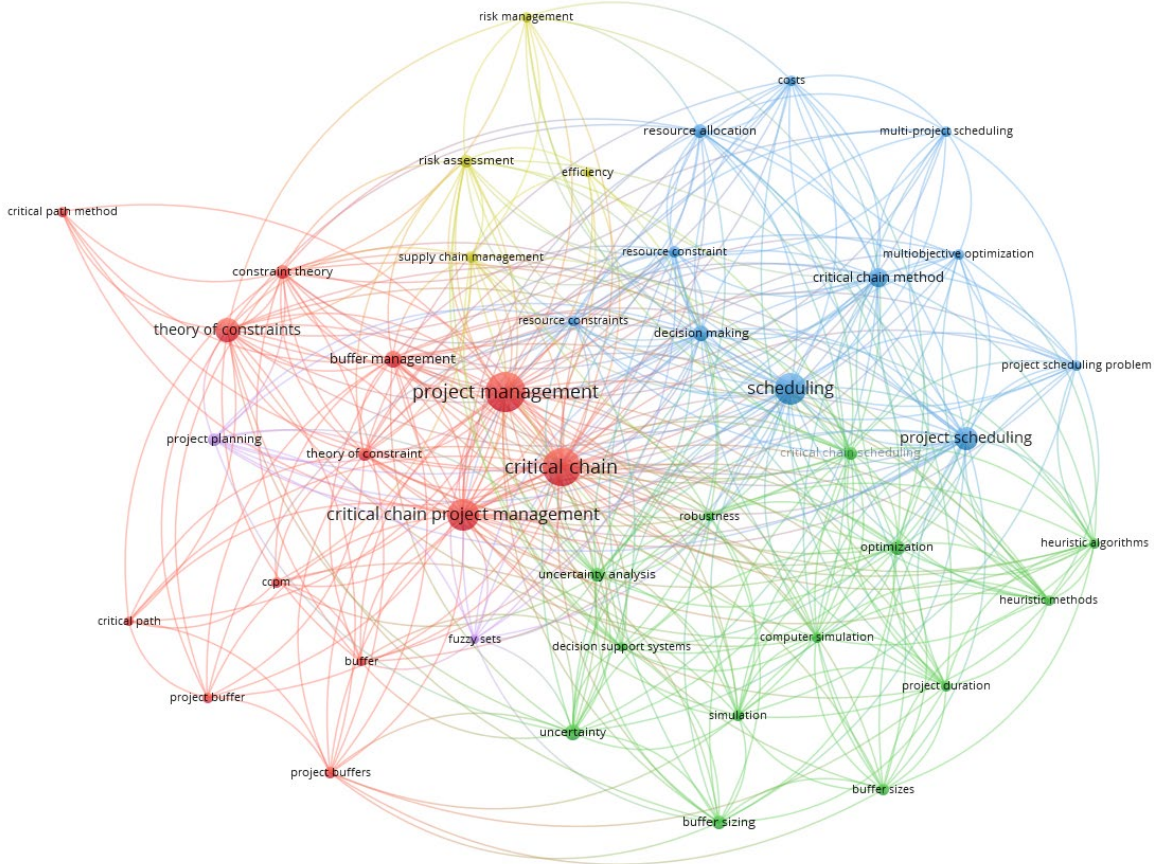

Fig. 1. Association graph obtained in VOSviewer

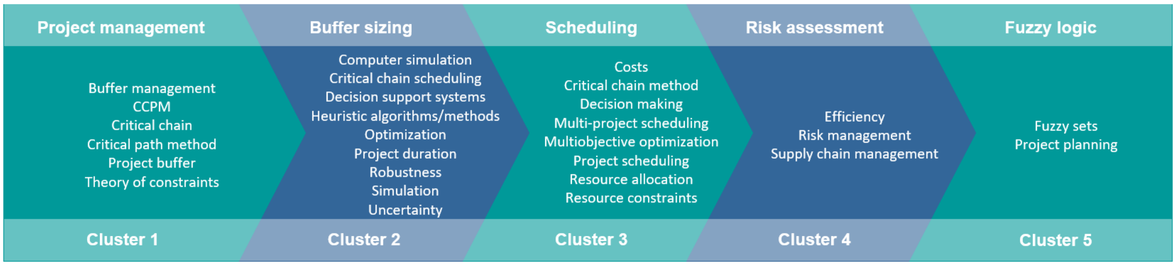

Fig. 2. Clusters obtained in VOSviewer

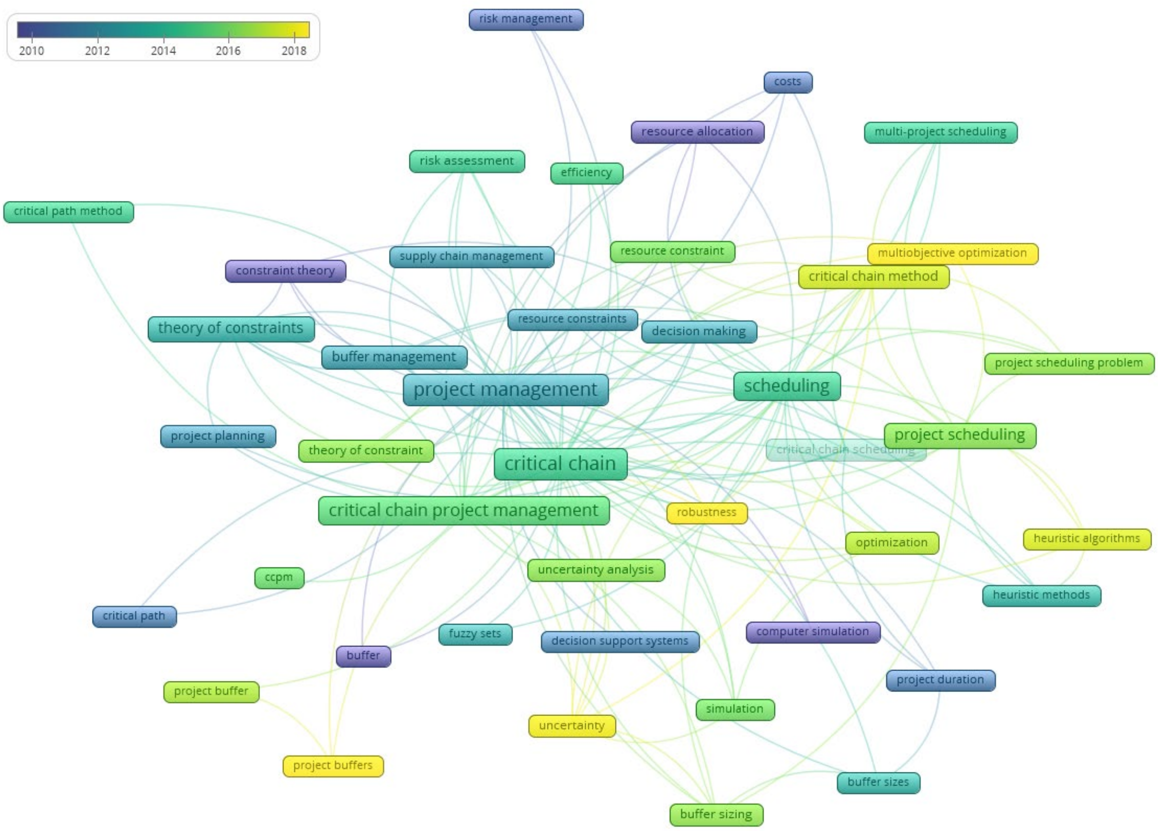

Fig. 3. Association graph with min. strength=3 obtained in VOSviewer

buffer management, and the theory of constraints. It includes issues related to project management, the operation of which is largely based on the previously mentioned concepts. Cluster 2, "Buffer sizing", is a group of concepts related to methods, techniques and tools supporting modelling and decision-making in operational project management, including buffer size estimation. In this cluster, the keywords "buffer sizing" and "buffer sizes" are linked with all other groups, which indicates the presentation of the studied concepts from the perspective of different approaches or analysed problems, such as: "computer simulation", "critical chain scheduling", "decision support systems", "heuristic algorithms/methods", "optimization", "project duration", "robustness", "simulation", "uncertainty". Terms in Cluster 3, "Scheduling", relate to project scheduling problems. This group has the term "critical chain method" with a total link strength of 84, which means that the context of research in this area is wide. Cluster 4, "Risk assessment", brings together concepts relating to risk management processes and their efficiency. Cluster 5, "Fuzzy logic", has only two concepts: "fuzzy sets" and "project planning", and it is a niche area of research in this source query.

The association graph presented in Fig. 3 indicates a successive development of issues related to a critical chain over several decades. The analysis was

Tab. 1. List of contemporary methods for estimating the time buffer size

Author	Year	Method assumptions
Goldratt E. M.	1997	Goldratt's 50 % rule is the simplest buffer estimation method. Buffer size constitutes half of the tasks' time sum on a path.
Newbold R.	1998	The root square error method (RSEM) extended Goldratt's concept by using the normal distribution. Buffers constitute risk aggregation in a project, and therefore, the uncertainty indices are used to calculate the buffer size.
Leach L. P.	2003	The sum of squares (SSQ) method assumes that the difference between the estimated optimistic and pessimistic duration constitutes a multiplication of standard deviation. This method uses the square root of the sum of squared differences for the estimated time deviation in calculating buffer sizes. The method differs from RSEM by the value of standard deviation.
Herroelen W. & Leus R.	2004	A method for calculating time buffer size in terms of solving the expected scheduling instability using cost minimisation task.
Van de Vonder S., Demeulemesser E., Herroelen W. & Leus R.	2005	
Tukel O. I., Rom W. O. & Eksioglu S. D.	2006	The adaptive procedure with density (APD) and the adaptive procedure with resource tightness (APRT) methods agree with the square root method assumptions for calculating time buffer size. The approach is extended by introducing a new coefficient.
Ashtiani B., Jalali G-R., Aryanezhad M-B. & Makui A. A.	2007	Ashtiani's root square error method (ARSEM) proposed a new method of buffer size calculation based on the RSEM method. This method is based on connecting the normal disintegration with the analysis of project risk parameters.
Tenera A. B.	2008	Monte Carlo simulation techniques are used for calculating the buffer size, which have been enriched by the ultimate deadline of the critical chain exceeding risk analysis.
Min Z. & Rongqiu C.	2008	Min's fuzzy approach buffer sizing technique with the fuzzy approach applied as a support tool in the planning process. The buffer size is determined based on the β index and the project risk level.
Shi Q. & Gong T.	2010	An improved method for determining the buffer size to overcome the resource constraints and deal with fuzzy uncertainties in project management. The method integrates three uncertainties, i.e., resource sharing, the complexity of the network and project managers' preference risk, to optimise the buffer configuration.
Fallah M., Ashitiani B. & Aryanezhad B.	2010	Log normal distribution applied in project buffer size calculation extended the approach of determining the time buffer size by introducing the uncertainty index.
Liu J. & Whangbo T-K.	2012	Statistical analysis in determining the time buffer size.
Slusarczyk A., Kuchta D., Verhulst P., Huyghe W., Lauryssen K. & Debal T.	2013	RISK CLASS ASSESSMENT (RCA) proposes determining the buffer size according to risk classes. The risk size is determined based on the level of risk, i.e., low, average, and high values.
Zhang J., Song X. & Díaz E	2014	Optimisation attributes are applied to calculate the time buffer size by applying the Monte Carlo method.
Kuchta D.	2014	The expert method is applied in determining project buffer size. Expert opinions have been expressed on the limits of buffer size and planned project completion.
Iranmanesh H., Mansourian F. & Kouchaki S.	2015	Density coefficients and risk aspects are used for calculating the time buffer size.
Poshdar M., González V., Raftery G., Orozco F., Romeo J. & Forcael E.	2016	Probabilistic method of buffer allocation (PBAL), which facilitates the final decision on the buffer size to be taken by project planners, based on their preferences concerning project completion time.
Zhang J., Song X. & Díaz E.	2016	A method for determining the buffer size based on complex resource tightness so as to better reflect the relations between activities and improve the accuracy of determining project buffers.
Taher S. F. & El-Korany T. M.	2016	The blue method estimates the buffer size according to probability and activity duration and is based on the distribution of variables. A, b, and m are described as optimistic, pessimistic, and the most probable activity duration, respectively.

Ghoddousi P., Ansari R. & Makui A.	2017	A multi-measure method for calculating the time buffer size considers path complexity, flexibility criteria, criticality index, and resistance measure. It facilitates the economic aspects of project buffers, i.e., the impact of external and internal risk factors on buffer size.
Roghanian E., Alipour M. & Rezaei M.	2018	A square root sum method modified using uncertainty indices.
Zohrehvandi S. & Khalilzadeh M.	2019	Hybrid approach applied in calculating time buffer size, connecting FMEA and APPT (resources saving methods).
Zarghami S. A., Gunawan I., Corral de Zubielqui G. & Baroudi B.	2020	A new method for determining the size of the project buffer for CCPM by developing a probabilistic measure obtained through a reliability analysis of project resources. In this method, buffer size was determined by assigning a scaling factor to the standard deviation of a chain.
She B., Chen B. & Hall N. G.	2021	A procedure for buffer sizing based on network decomposition. First, the size of a feeding buffer is determined from all associated noncritical chains. Second, the project buffer incorporates safety margins outside the critical chain by comparing feeding chains with their parallel critical counterparts.
Li H., Cao Y., Lin Q. & Zhu H.	2022	Full-factor design of experiments and Monte Carlo simulation used to construct the required dataset. Support vector regression is adopted to train the project buffer prediction model.

Source: Elaborated by the author based on (Ashtiani et al., 2007; Fallah et al., 2010; Ghoddousi et al., 2017; Goldratt, 1997; Herroelen & Leus, 2004; Liu & Whangbo, 2012; Iranmanesh et al., 2015; Kuchta, 2014; Leach, 2003; Li et al., 2022; Min & Rongqiu, 2008; Newbold, 1998; Poshdar et al., 2016; Roghanian et al., 2018; She et al., 2021; Shi & Gong, 2010; Slusarczyk et al., 2013; Taher & El-Korany, 2016; Tenera, 2008; Tukel et al., 2006; Van de Vonder et al., 2005; Zarghami et al., 2020; Zhang et al., 2014, 2016; Zohrehvandi & Khalilzadeh, 2019).

narrowed to "min. strength" = 3 that determines, respectively, the minimum strength of links displayed in the visualisation.

The new (within one source query no sooner than after 2016) unrelated or weakly related terms include "project buffer", "buffer sizing", "uncertainty", "robustness", "project scheduling", "optimization", "heuristic algorithms", which may prove a research gap in project programming phenomenon, applying CCPM and a need to focus on determining the buffer size, considering the uncertainty conditions and robust scheduling problems.

The study showed a strong correlation between the terms "critical chain" and "project management", "scheduling", "theory of constraints", "buffer management", and "uncertainty". A noteworthy aspect is the increasing occurrence of phrases "robustness" and "optimization" concerning project scheduling, which indicates that these issues are gaining importance not only in the context of task scheduling in the production system but are increasingly used in project management. Robustness is a measure of the result after the application of a procedure under uncertainties or after the appearance of uncertainty, e.g., relative to the operation duration of the task, the availability of the resource, etc. The robustness of a schedule is, therefore, a way to characterise its performance. The method for determining the buffer size can be important for obtaining the right flexibility and robustness in project scheduling.

The literature survey showed a frequent occurrence of the critical chain topic with the terms "project duration", "decision-making", and "resource allocation". These dependencies may indicate the need to develop new heuristic methods to support decision-making in this area, as well as the importance of meeting the project deadline under conditions of uncertainty. In connection with these issues, the use of fuzzy logic gives promising results, but it is still a niche area of research.

Pursuant to the critical chain method, the determination of buffer size is an inherent element in project scheduling. The literature on the issue includes numerous methods for determining the buffer size. Some are very simple, and others require advanced statistical and mathematical methods. Table 1 presents an analysis of actual methods for estimating the time buffer size.

As outlined in the table and indicated by Zohrehvandi and Soltani (2022), buffer size in critical chain scheduling has been a subject of research for several years. Most researchers focused on modifying the most popular methods for calculating the time buffer size, such as the 50 % rule, SSQ, etc. Apart from modified previously established methods, several individual methods can be found in the existing literature on estimating the time buffer size, e.g., RSE, APD, APRT, MIN'S FUZZY, or BLUE. Also, attempts were made to determine the most efficient method, e.g., by Altarazi and Bao (2015) and Moussa, El-Korany, Etman, and Tahir (2016). Results indicate that methods such as the 50 % rule, SSQ and RSEM are more efficient in estimating the time buffer size when the task character is known, while in other cases, it is better to apply methods based on simulations.

The premises above and the fact that not all methods for evaluating the buffer size consider the project execution probability at a level of at least 90 % provided the basis for a new model developed and described in this paper. The application of fuzzy numbers and normal distribution factors may constitute a suitable model for buffer size and is further explored in this paper.

2. Research methods

The analysed research problem focuses on the method for determining the project buffer size, which would guarantee a 90 % probability of timely project execution, also under uncertainty conditions and robust scheduling problems.

Project scheduling methods are frequently based on network models, which assume a certain precedence relation of particular jobs/processes. Precedence relations, employed to model technological and organisational relations between jobs, are established at the model-building phase and result from the technology and limitations in the scope of realised jobs or specified resource allocation. The given type of schedule assumes no variables and is, therefore, modelled using deterministic analysis networks (DAN) of a determined logical structure.

Performance determinant factors of a project can be represented by the one-node network. The precedence relation between production jobs can be modelled using a connected directed acyclic unigraph $G=\langle V, E\rangle$ with one start and end node, where $V=\{1, 2, K, n\}$ denotes the set of project tasks (in the network described as an activity), and $E\subset V\times V$ is a binary relation determining the precedence relation between activities.

The fuzzy model for estimating the project time buffer includes the application of two elements. First, triangular fuzzy numbers are to be applied to estimate the time buffer size with different project completion probabilities. It was determined that B' is a time buffer fuzzy number (project or feed) with the following definition: $B_i' = \left(\overline{b_\iota},\ \overline{\overline{b}}_\iota,\ \widetilde{b_\iota}\right), \bar{b} < \bar{\bar{b}} < \breve{b}$, where $\bar{\bar{b}}$ is the buffer size at which the project has a 90 % probability of timely execution, and the parameter $\bar{b}$ defines the buffer size at an 85 % probability, and $\tilde{b}$ at a 95 % probability of timely project execution.

Second, fuzzy number sets are selected according to the probability of project execution based on the normal distribution factor (Nafkha, 2016; Ravalji & Deshpande, 2014):

$$x = \frac{T_d - T_e}{\delta_c}, \qquad (1)$$

where: x is the time scaled to N [0,1], T_e is the planned project execution time, estimated according to CCPM, T_d is the project execution time, resulting from previous scheduling ($t_{0.9}$), and δ_c is the standard deviation. Due to the fact that time T_e is a sum of aggressive times (T_e') and buffer size (B), formula (1) was transformed as follows to determine the triangular fuzzy numbers:

$$B = T_d - x\delta_c - T_e' \qquad (2)$$

The assignment function of the analysed model defines time buffer size with a determined probability of timely project execution. The assignment function formula is as follows (Molinari, 2016; Wang, 2015):

$$\mu(B') = \begin{cases} 0 & dla \quad B' \le \bar{b} \\ \dfrac{B' - \bar{b}}{\bar{\bar{b}} - \bar{b}} & dla \quad \bar{b} < B' < \bar{\bar{b}} \\ \dfrac{\tilde{b} - B'}{\tilde{b} - \bar{\bar{b}}} & dla \quad \bar{\bar{b}} < B' < \tilde{b} \\ 0 & dla \quad B' \ge \tilde{b} \end{cases} \qquad (3)$$

Fuzzy sets conclusion has been assumed for the model according to the following formula:

$$\mu_{B_{i-1} \wedge B_i}(B') = \min\left(\mu_{B_{i-1}}(B'), \mu_{B_i}(B')\right) \qquad (4)$$

Defuzzification is necessary to determine a number (as a time buffer value) to reflect the assumptions of the critical chain method and to meet the fuzzy model rule. It may be done using the following methods (Abbasbandy et al., 2004; Hellendoorn & Thomas, 1993; Saade & Diab, 2004; Pedrycz, 1993; Roychowdhury & Wang, 1996): first maximum, last maximum, middle maximum (middle of the best section), and the centre of gravity and height. This paper used the method of the "middle best sector" to calculate the time buffer size. First, it is necessary to find a section for which the assignment functions are at maximum. If there are several of them, the first one (the last and the longest) is selected. If there is no such section, the first peak value is assumed. If there is such a section, the middle

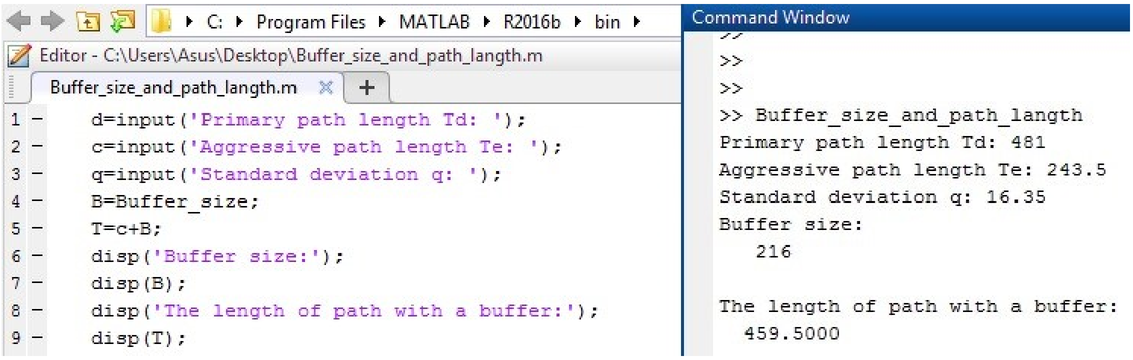

Fig. 4. Application of the project buffer size calculation developed in the MATLAB program

as the buffer size is assumed according to the formula: $z = a + b/2$, where a is the first maximum value of the membership function, and b is the second maximum value of the function.

As the described fuzzy model for estimating the buffer size requires that the project manager applies advanced mathematical tools, an application in MATLAB has been developed. The application determines the time buffer after adding the primary path length Td, the aggressive path length *Te*', and the standard deviation. Fig. 4 presents a view from the application developed in MATLAB.

3. Research results

The verification of the developed fuzzy model for estimating the time buffer size of a project has been carried out using technical preparation for a new product in one of the Polish enterprises as an example. Table 2 presents the project work structures.

The project consists of three stages and twenty-six tasks, and three milestones. Table 3 presents a listing of safe and aggressive duration times of individual tasks. Aggressive times were identified based on historical data and the use of the inverse of the cumulative normal distribution. The calculations assumed a probability of 50 %. Table 3 information also shows whether a task is critical and a milestone. Fig. 5 presents an example of a time buffer location in technical preparation production project scheduling. In this case, the critical chain consists of 22 tasks: 1, 2.1, 2.2, 4, 5.1, 5.3, 5.4, 5.5, 6.1, 6.2, 6.4, 6.5, 7.1, 7.4, 7.5, and 8. The project buffer (PB) has been put at the end of the path. There are also four noncritical paths, in which the task sequence is as follows: 3.2–3.3, 6.6, 6.7–6.8, and 7.2–7.3. Feed buffers FB1, FB2, FB3, and FB4 have been placed at the end of the noncritical paths.

After locating time buffers in scheduling, it is necessary to calculate their size. For this purpose, the application in MATLAB has been used. First, three triangular fuzzy numbers have been determined for the project buffer based on formula (2):

$$B'_{95\%} = (199.6; 210.6; 216.5),$$
$$B'_{90\%}(210.6; 216.5; 220.5),$$
$$B'_{85\%} = (216.5; 220.5; 223.7).$$

According to fuzzy logic, the buffer size for the example under consideration is 216 days with a standard deviation of 16.35. The standard deviation was calculated based on historical data. The estimated project time, according to the critical chain method, is 459.6 days and is 21.5 days shorter than in preliminary scheduling (about 4.5 % reduction). Unlike the method of half times sum on the path, fuzzy sets may not guarantee the shortening of the whole project by 25 %, but they do guarantee at least 90 % timely project execution.

An analogous procedure is applied for feed buffer size calculation. The first feed buffer has been identified after Task 3.3. Path 3.2–3.3 has been adopted for the calculation instead of path 3.1–3.3, as the first path is longer than the second. The first buffer size is 8.9 days, and the second buffer size is 11.5 days. The third corresponds to 11.5 days, while the fourth is 13 days. Following the CCPM method, the critical chain cannot change after the introduction of feed buffers into technical project preparation scheduling. This is witnessed in this procedure, and hence, the size of the buffers can be acknowledged as accurate.

Tab. 2. Project's work structure for the preparation of product production in the form of a list of functions

WBS	Name of stage/task
1	**Decision on project commencement**
2	**Market research**
2.1	Basic research
2.2	Applied research
3	**Economic analyses**
3.1	Project preliminary cost estimation
3.2	Product sale future income estimation
3.3	NPV index estimation
4	**Decision on product production preparation commencement**
5	**Structural preparation of new product production**
5.1	Construction assumptions development
5.2	New product preliminary design development
5.3	Technical design development
5.4	Prototype execution and testing
5.5	Execution design of construction development
6	**Technological preparation of a new product**
6.1	Technological plan concept development
6.2	Determining technological operations and their execution sequence
6.3	Selection of production machinery and equipment
6.4	Determining workshop support
6.5	Workshop special support structures development
6.6	Determining staff qualifications
6.7	Standards (quantities) of materials and standards of work time (operations)
6.8	Selection of technological process quality control
7	**Organisational preparation of new product production**
7.1	Production preparation
7.2	Determining supplies for new product production – resources and materials
7.3	Training – staff preparation for production
7.4	Market preparation for the production
7.5	New product promotion preparation
8	**Commencement of serial production**

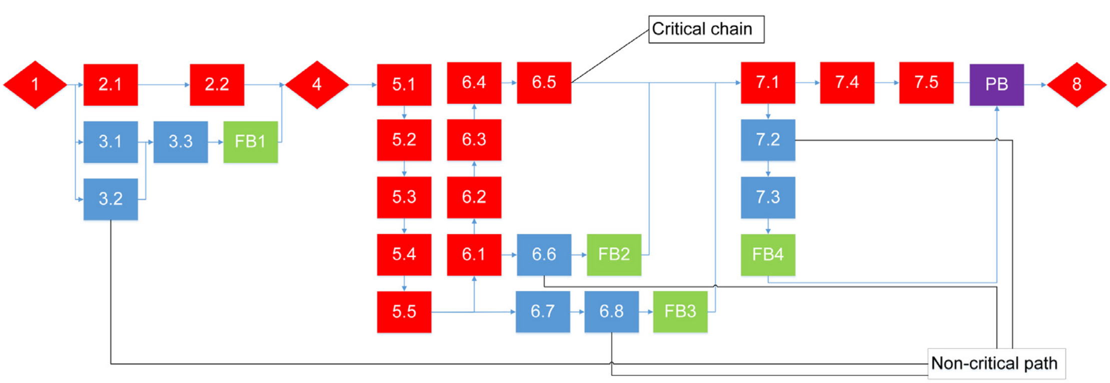

Fig. 5. Network of dependencies on the application of the critical chain method of production preparation

Tab. 3. List of task durations and relations between tasks

WBS	**Predecessor**	$T_{0.9}$ [days]	$T_{0.5}$ [days]	**Critical task**	**Milestone**
1		**0**	**0**	**Yes**	**Yes**
2		**89**	**45**	**Yes**	**No**
2.1	1	33	17	Yes	No
2.2	2.1	56	28	Yes	No
3		**24**	**12**	**No**	No
3.1	1	8	4	No	No
3.2	1	18	9	No	No
3.3	3.1;3.2	6	3	No	No
4	**2.2;3.3**	**1**	**0.5**	**Yes**	**Yes**
5		**182**	**92**	**Yes**	**No**
5.1	4	29	15	Yes	No
5.2	5.1	46	23	Yes	No
5.3	5.2	48	24	Yes	No
5.4	5.3	32	16	Yes	No
5.5	5.4	27	14	Yes	No
6		**103**	**53**	**Yes**	**No**
6.1	5.5	18	9	Yes	No
6.2	6.1	27	14	Yes	No
6.3	6.2	17	9	Yes	No
6.4	6.3	13	7	Yes	No
6.5	6.4	28	14	Yes	No
6.6	6.1	35	18	No	No
6.7	5.5	18	9	No	No
6.8	6.7	12	6	No	No
7		**106**	**53**	**Yes**	**No**
7.1	6.6;6.8;6.5	28	14	Yes	No
7.2	7.1	14	7	No	No
7.3	7.2	21	11	No	No
7.4	7.1	34	17	Yes	No
7.5	7.4	44	22	Yes	No
8	**7.3;7.5**	**0**	**0**	**Yes**	**Yes**

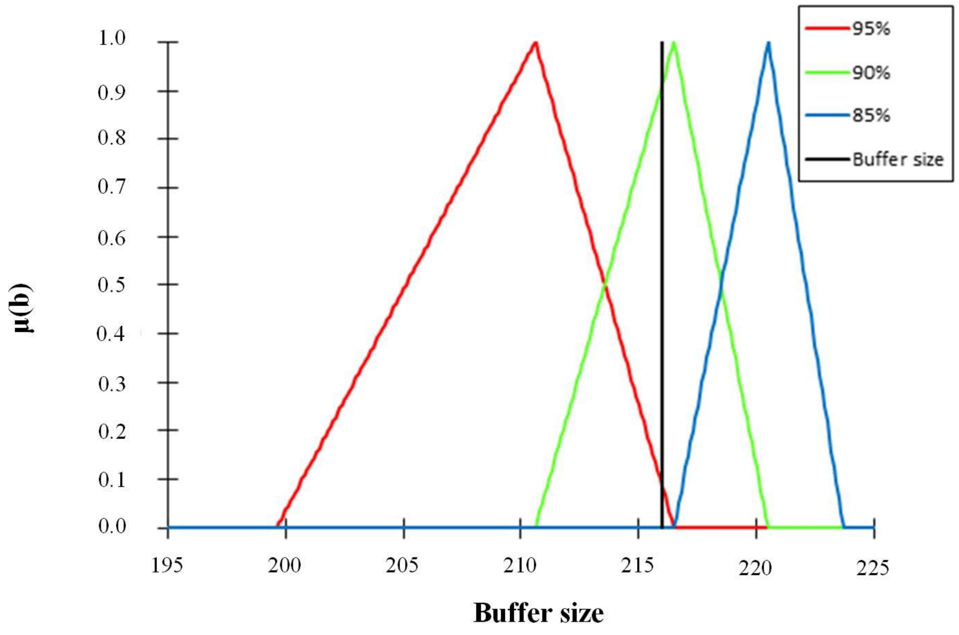

Fig. 6. Assignment function of triangular fuzzy numbers of project buffer size with defuzzification results

4. Discussion of the results

Table 4 presents a comparison of several methods selected for determining time buffer size to compare the proposed method with other methods described in the existing literature. The following methods have been selected for the research:

The half times sum at the aggressive scheduling path method. The buffer size is calculated using the following dependency (Ravalji & Deshpande, 2014):

$$Bufor = \frac{1}{2}\sum_{i=1}^{n} t_{0.5_i} \quad (5)$$

The method of square root of squared sum difference between safe time ($t_{0.9}$) and aggressive time ($t_{0.5}$). The dependency is presented in the following formula (Slusarczyk et al., 2013):

$$Bufor = \sqrt{\sum_{i=1}^{n}(t_{0.9_i} - t_{0.5_i})^2} \quad (6)$$

The root square error method (RESM) describes two square roots of the deviation sum between safe time and aggressive time. The buffer is calculated using the following formula (Ravalji & Deshpande, 2014):

$$Bufor = 2 * \sqrt{\sum_{i=1}^{n}\sigma^2} \quad (7)$$

Where:
σ — the difference between safe and aggressive time,
$t_{0,9}$ — estimated safe time and tasks,
$t_{0,5}$ — estimated aggressive time and tasks,
n — number of tasks in a path.

The listing presented in Table 4 indicates that the shortest planned project duration time (308.9 days) can be reached using the square root of the squared sum differences method between safe time ($t_{0.9}$) and aggressive time ($t_{0.5}$). The application of the method

Tab. 4. Listing of time buffer size determining methods

Buffer type	Path	Path length $T_{0.9}$ [days]	Path length $T_{0.5}$ [days]	Dependence	Buffer size [days]	Planned path time [days]	Change path time [days]	Change path time [%]
PB	1-2.1-2.2-4-5.1-5.2-5.3-5.4-5.5-6.1-6.2-6.3-6.4-6.5-7.1-7.4-7.5-8	481	243.5	(2)	216.0	459.5	-21.5	-4.5
				(5)	121.8	365.3	-115.7	-24.1
				(6)	65.4	308.9	-172.1	-35.8
				(7)	130.9	374.4	-106.6	-22.2
FB1	3.2-3.3	24.0	12.0	(2)	8.9	20.9	-3.1	-12.9
				(5)	6.0	18.0	-6.0	-25.0
				(6)	9.5	21.5	-2.5	-10.4
				(7)	19.0	31.0	+7.0	+29.2
FB2	6.6	35.0	18.0	(2)	11.5	29.5	-5.5	-15.7
				(5)	9.0	27.0	-8.0	-22.9
				(6)	17.0	35.0	-0.0	0,0
				(7)	34.0	52.0	+17.0	+48.6
FB3	6.7-6.8	30.0	15.0	(2)	11.5	26.5	-3.5	-11.7
				(5)	7.5	22.5	-7.5	-25.0
				(6)	10.8	25.8	-4.2	-14.0
				(7)	21.6	36.6	+6.6	+22.0
FB4	7.2-7.3	35.0	18.0	(2)	13.0	31.0	-4.0	-11.4
				(5)	9.0	27.0	-8.0	-22.9
				(6)	12.2	30.2	-4.8	-13.7
				(7)	24.4	42.4	+7.4	+21.1

Tab. 5. Buffer size, according to the probability of timely project execution

Probability	The value of the normal distribution function	Buffer size	Probability	The value of the normal distribution function	Buffer size
0.55	0.13	235.37	0.77	0.74	225.40
0.56	0.16	234.88	0.78	0.78	224.75
0.57	0.18	234.56	0.79	0.82	224.09
0.58	0.21	234.07	0.80	0.85	223.60
0.59	0.23	233.74	0.81	0.88	223.11
0.60	0.26	233.25	0.82	0.92	222.46
0.61	0.28	232.92	0.83	0.96	221.80
0.62	0.31	232.43	0.84	1.00	221.15
0.63	0.34	231.94	0.85	1.04	220.50
0.64	0.36	231.61	0.86	1.09	219.68
0.65	0.39	231.12	0.87	1.13	219.02
0.66	0.42	230.63	0.88	1.18	218.21
0.67	0.44	230.31	0.89	1.23	217.39
0.68	0.47	229.82	0.90	1.29	**216.41**
0.69	0.50	229.33	0.91	1.35	**215.43**
0.70	0.53	228.83	0.92	1.42	**214.28**
0.71	0.56	228.34	0.93	1.48	**213.30**
0.72	0.59	227.85	0.94	1.56	**211.99**
0.73	0.62	227.36	0.95	1.65	**210.52**
0.74	0.65	226.87	0.96	1.76	**208.72**
0.75	0.68	226.38	0.97	1.89	**206.60**
0.76	0.71	225.89	0.98	2.06	**203.82**

reduces the total project time by over 35 %, which may mean that such an optimistic determination of the buffer size can lead to reduced chances of timely project completion. A similar situation occurs with the 50 % rule method and the RSEM. Moreover, it should be considered whether the feed buffer sizes will change the critical chain flow. The analysis demonstrates that if the RSEM method is applied to determine the time buffer size, the critical chain will change, and hence, the method should be excluded in this case.

Analysis of the research results has been extended by checking whether the time buffer sizes determined according to these methods align with the main principle of CCPM, i.e., whether the project meets the minimum of a 90 % probability of timely project execution, following time reduction and introduction of buffers. To determine this, the project buffer size value is assessed using the normal distribution factor formula. Table 5 presents the calculation results.

This paper calculates that the project buffer should be between 203.82 and 216.41 days to meet the CCPM method requirements. The verification of whether the methods met the principle found only one such method, i.e., the project size estimating model, thereby substantiating the application of the model developed.

Research results prove that the model developed for estimating the time buffer size guarantees at least a 90 % probability of timely project execution. It is, therefore, necessary to rationally analyse the obtained buffer values and select a method that may guarantee at least a 90 % probability of timely project execution.

Conclusions

The presented research aimed at solving the following research issue: the time buffer size in the critical chain programme does not guarantee a 90 % probability of timely project execution. To solve the problem, the following research questions have been asked:

- What time buffer size estimation methods have been described in the literature?
- Do the methods described in the source literature guarantee a 90 % probability of timely project execution?
- Can fuzzy numbers be applied for determining time buffer size? Why are they worth applying?
- How can a 90 % probability of timely project execution be guaranteed?
- Will elaborating on a fuzzy model for determining the time buffer size guarantee a 90 % probability of timely project execution?

An answer to the first two research questions has been obtained from a source literature analysis, indicating that many methods are available for estimating the time buffer size; however, none of them guarantees a 90 % probability of timely execution. This encouraged the authors of this article to start searching for a new method for estimating the time buffer size. The analysis commenced from the rule that the total project execution time with time buffers must guarantee a 90 % probability of timely project execution. As projects are executed under uncertainty conditions and values for buffer size estimation are frequently inaccurate, it was proposed to apply triangular fuzzy numbers. This answered the third and fourth research questions. The analyses allowed for the development of a fuzzy model for determining the time buffer size. To achieve conclusions of fuzzy sets, the model applied a method of the "middle best sector" (MBS). The model was applied in the MATLAB software to estimate the buffer size using the Project Manager.

The model was applied in practice in a technical production preparation project for a new product in one Polish enterprise. The research results indicate that the developed fuzzy model for determining the time buffer size is efficient as it shortens the total project duration while preserving aggressive task times and guaranteeing a 90 % probability of project timely execution. As a result, unwanted situations can be eliminated from the project, such as the student syndrome, Parkinson's law, overestimating of task duration, and multitasking. Moreover, the developed model was compared with other methods, such as half of the time total of a path, the sum of squares (SSQ), and the root square error method (RSEM). The analysis results indicate that the developed model may not shorten the total project duration time by 25 %, such as the method of half of the times total of a path, or by 35 %, such as the SSQ method, but merely by 5 %. However, it guarantees a 90 % probability of timely project execution. Thus, a positive answer was received to the last research question regarding the guaranteed 90 % probability for timely project execution. Hence, the research problem has been solved.

As the research results are satisfactory and characterised by possible practical application in projects, it is expected that further future research will be performed to search for the possibility of the development and application of a fuzzy model in determining time buffer size in a critical chain programme.

Literature

Abbasbandy, S., Viranloo, T. A., López-Pouso, Ó., & Nieto, J. J. (2004). Numerical Methods for Fuzzy Differential Inclusions. *Computer and Mathematics with Applications, 48*, 1633-1641. doi: 10.1016/j.camwa.2004.03.009

Altarazi, F., & Bao, H. (2015). Investigating the Impact of Buffer Size in Critical Chain Management. *Flexible Automation and Intelligent Manufacturing (FAIM2015)*, 1-8.

Ashtiani, B., Jalali, G. R., Aryanezhad, M. B., & Makui, A. (2007). A new approach for buffer sizing in critical chain scheduling. In *Proceedings of the IEEE International Conference on Industrial Engineering and Engineering Management*, Singapore, 2–4 December 2007, 1037-1041.

Atkinson, R. (1999). Project Management: Cost, Time and Quality, Two Best Guesses and a Phenomenon, It's Time to Accept Other Success Criteria. *International Journal of Project Management, 17*, 337-342. doi: 10.1016/S0263-7863(98)00069-6

Cserháti, G., & Szabó, L. (2014). The relationship between success criteria and success factors in organizational event projects. *International Journal of Project Management, 32*, 613-624. doi: 10.1016/j.ijproman.2013.08.008

Fallah, M., Ashitiani, B., & Aryanezhad, B. (2010). Critical chain project scheduling: utilizing uncertainty for buffer sizing. *International Journal of Research and Reviews in Applied Sciences, 3*(3), 280-289.

Ghoddousi, P., Ansari, R., & Makui, A. (2017). A risk-oriented buffer allocation model based on critical chain project management. *KSCE Journal of Civil Engineering, 21*, 1536-1548. doi: 10.1007/s12205-016-0039-y

Goldratt, E. M. (1997). *Critical Chain*. Great Barrington: The North River Press Publishing Corporation.

Hass, K. B. (2010). Managing complex projects that are too large, too long and too costly. Retrieved from https://www.projecttimes.com/articles/managing-complex-projects-that-are-too-large-too-long-and-too-costly.html

Hellendoorn, H., & Thomas, C. (1993). Defuzzification in fuzzy controllers. *Journal of Intelligent and Fuzzy Systems, 1*(2), 109-123. doi: 10.3233/ifs-1993-1202

Herroelen, W., & Leus, R. (2004). The construction of stable project baseline schedule. *European Journal of Operational Research, 156*, 550-565. doi: 10.1016/S0377-2217(03)00130-9

Iranmanesh, H., Mansourian, F., & Kouchaki, S. (2015). Critical chain scheduling: a new approach for feeding buffer sizing. *International Journal of Operational Research, 25*(1), 114-130. doi: 10.1504/IJOR.2016.073254

Izmailov, A., Korneva, D., & Kozhemiakim, A. (2016). Project management using the buffers of time and resources. *Procedia-Social and Behavioral Sciences, 235*, 189-197. doi: 10.1016/j.sbspro.2016.11.014

Jugdev, K., & Müller, R. (2005). A retrospective look at our evolving understanding of project success. *Project Management Journal, 36*(4), 9-31. doi: 10.1177/875697280503600403

Kuchta, D. (2014). A new concept of project robust schedule – use of buffers. *Information Technology and Quantitative Management (ITQM 2014), Procedia Computer Science, 31*, 957-965. doi: 10.1016/j.procs.2014.05.348

Leach, L. P. (1999). Critical chain project management improves project performance. *Project Management Journal, 30*(2), 39-51. doi: 10.1177/875697289903000207

Leach, L. P. (2003). Schedule and cost buffer sizing: How to account for performance and your model. *Project Management Journal, 34*(2), 34-47. doi: 10.1177/875697280303400205

Leach, L. P. (2005). *Lean Project Management: Eight Principles for Success*. Boise Idaho: Advanced Projects Inc.

Leach, L. P. (2014). *Critical Chain Project Management* (Third Edition). Boston: Artech House.

Li, H., Cao, Y., Lin, Q., & Zhu, H. (2022). Data-driven project buffer sizing in critical chains. *Automation in Construction, 135*. doi: 10.1016/j.autcon.2022.104134

Liu, J., & Whangbo, T.-K. (2012). A study on the buffer sizing method of CCPM technique using statistical analysis. In: Lee G., Howard D., Ślęzak D., Hong Y.S. (Eds.), *Convergence and Hybrid Information Technology. ICHIT 2012. Communications in Computer and Information Science, 310*. Springer, Berlin, Heidelberg.

Martens, C. D. P., Machado, F. J., Martens, M. L., Oliveira e Silva, T. Q. P., & de Freitas, H. M. R. (2018). Linking entrepreneurial orientation to project. *Journal of Project Management, 36*(2), 255-266. doi: 10.1016/j.ijproman.2017.10.005

Min, Z., & Rongqiu, C. (2008). Buffer sized technique in critical chain management: A fuzzy approach. In *Wireless Communications. Networking and Mobile Computing, 2008. WiCOM '08. 4th International Conference*, 12–14 October, 1-4.

Molinari, F. (2016). A new criterion of choice between generalized triangular fuzzy numbers. *Fuzzy Sets and Systems, 296*, 51-69. doi: 10.1016/j.fss.2015.11.022

Moussa, D. A., El-Korany, T. M., Etman, E. E., & Taher, S. F. (2016). Evaluation of critical chain buffer sizing techniques. *AICSGE, Egypt*, 1-10.

Müller, R., & Turner, R. (2007). The influence of project managers on project success criteria and project success by type of project. *European Management Journal, 25*(4), 298-309. doi: 10.1016/j.emj.2007.06.003

Nafkha, R. (2016). The PERT method in estimating project duration. *Information Systems in Management, 5*(4), 542-550.

Newbold, R. (1998). *Project Management in the Fast Lane – Applying the Theory of Constraints*. Boca Raton: The St. Lucie Press.

Pedrycz, W. (1993). *Fuzzy Control and Fuzzy Systems* (Second Extended Edition). England: Research Studies Press.

Poshdar, M., González, V., Raftery, G., Orozco, F., Romeo, J., & Forcael, E. (2016). A probabilistic-based method to determine optimum size of project buffer in construction schedules. *Journal of Construction Engineering and Management, 142*(10). doi: 10.1061/(ASCE)CO.1943-7862.0001158

Project Management Institute. (2013). *A Guide to the Project Management Body of Knowledge* (5th edition). Newtown Square, USA: PMI.

Ravalji, J. M., & Deshpande, V. A. (2014). Comparative study of alternatives for 50% rule in critical chain project management. In *International Conference on Design, Manufacturing and Mechatronics* (pp. 1–10). KJEI's Trinity College of Engineering and Research.

Raz, T., Barnes, R., & Dvir, D. (2003). A critical look at critical chain project management. *Project Management Journal, 34*(4), 24-32. doi: 10.1177/875697280303400404

Roghanian, E., Alipour, M., & Rezaei, M. (2018). An improved fuzzy critical chain approach in order to face uncertainty in project scheduling. *International Journal of Construction Management, 18*(1), 1-13. doi: 10.1080/15623599.2016.1225327

Roychowdhury, S., & Wang, B.-H. (1996). Cooperative neighbors in defuzzification. *Fuzzy Sets and Systems, 78*(1), 37-49. doi: 10.1016/0165-0114(95)00077-1

Saade, J. J. M., & Diab, H. B. (2004). Defuzzification methods and new techniques for fuzzy controllers. *Iranian Journal of Electrical and Computer Engineering, 3*(2), 161-174.

Sebestyen, Z. (2017). Further considerations in project success. *Procedia Engineering, 196*, 571-577. doi: 10.1016/j.proeng.2017.08.032

Serrador, P., & Turner, R. (2014). The relationship between project success and project efficiency. *Procedia-Social and Behavioral Sciences, 119*, 75-84. doi: 10.1016/j.sbspro.2014.03.011

She, B., Chen, B., & Hall, N. G. (2021). Buffer sizing in critical chain project management by network decomposition. *Omega, 102*. doi: 10.1016/j.omega.2020.102382

Shenhar, A. J., Levy, O., Dvir, D., & Maltz, A. C. (2001). Project success: a multidimensional strategic concept. *Long Range Planning, 34*(6), 699-725. doi: 10.1016/S0024-6301(01)00097-8

Shi, Q., & Gong, T. (2010). An improved project buffer sizing approach to critical chain management under resources constraints and fuzzy uncertainty. *Artificial Intelligence and Computational Intelligence, IEEE. AICI '09. International Conference on*. doi: 10.1109/AICI.2009.192

Slusarczyk, A., Kuchta, D., Verhulst, P., Huyghe, W., Lauryssen, K., & Debal, T. (2013). A comparison of buffer sizing techniques in the critical chain method. *Journal of Automation Mobile Robotics and Intelligent Systems, 7*(3), 43-56.

Spalek, S. (2014). Success factors in project management: Literature review. *Proceedings of 8th International Technology Education and Development Conference INTED2014*, Valencia, Spain (pp. 4828–4835).

Taher, S. F., & El-Korany, T. M. (2016). Critical chain project management – a critique. *1st International Conference Sustainable Construction and Project Management*, Egypt.

Tenera, A. B. (2008). Critical chain buffer sizing: a comparative study. Paper presented at *PMI® Research Conference: Defining the Future of Project Management*, Warsaw: Newtown Square, PA: Project Management Institute.

The Standish Group (2013). *The Chaos Manifesto. Think Big. Act Small.*

Tukel, O. I., Rom, W. O., & Eksioglu, S. D. (2006). An investigation of buffer sizing techniques in critical chain scheduling. *European Journal of Operational Research, 172*(2), 401-416. doi: 10.1016/j.ejor.2004.10.019

Turner, R., & Zolin, R. (2012). Forecasting success on large projects: Developing reliable scales to predict multiple perspectives by multiple stakeholders over multiple time frames. *Project Management Journal, 43*(5), 87-99. doi: 10.1002/pmj.21289

Urbański, M., Haque, A., & Oino, I. (2019). The moderating role of risk management in project planning and project success: Evidence from construction businesses of Pakistan and the UK. *Engineering Management in Production and Services, 11*(1), 23-35. doi: 10.2478/emj-2019-0002

Van de Vonder, S., Demeulemesser, E., Herroelen, W., & Leus, R. (2005). The use of buffers in project management: The trade-off between stability and makespan. *International Journal of Production Economics, 97*, 227-240. doi: 10.1016/j.ijpe.2004.08.004

Wang, Y.-J. (2015). Ranking triangle and trapezoidal fuzzy numbers based on the relative preference relations. *Applied Mathematical Modelling, 39*(2), 586-599. doi: 10.1016/j.apm.2014.06.011

Young, R., & Poon, S. (2013). Top management support—almost always necessary and sometimes sufficient for success: Findings from a fuzzy set analysis. *International Journal of Project Management, 31*(7), 943-957. doi: 10.1016/j.ijproman.2012.11.013

Zarghami, S. A., Gunawan, I., Corral de Zubielqui, G., & Baroudi, B. (2020). Incorporation of resource reliability into critical chain project management buffer sizing. *International Journal of Production Research, 58*(20), 6130-6144. doi: 10.1080/00207543.2019.1667041

Zhang, J., Song, X., & Díaz, E. (2014). Buffer sizing of critical chain based on attribute optimization. *Concurrent Engineering, 22*(3), 253-264. doi: 10.1177/1063293X14541286

Zhang, J., Song, X., & Díaz, E. (2016). Project buffer sizing of a critical chain based on comprehensive resource tightness. *European Journal of Operational Research, 248*(1), 174-182. doi: 10.1016/j.ejor.2015.07.009

Zohrehvandi, S., & Khalilzadeh, M. (2019). APRT-FMEA buffer sizing method in scheduling of a wind farm construction project. *Engineering, Construction and Architectural Management, 26*(6), 1129-1150. doi: 10.1108/ECAM-04-2018-0161

Zohrehvandi, S., & Soltani, R. (2022). Project scheduling and buffer management: A comprehensive review and future directions. *Journal of Project Management, 7*(2), 121-132. doi: 10.5267/j.jpm.2021.9.002