The current issue and full text archive of this journal is available on Emerald Insight at:
www.emeraldinsight.com/0969-9988.htm

APRT-FMEA buffer sizing method in scheduling of a wind farm construction project

Shakib Zohrehvandi and Mohammad Khalilzadeh
Department of Industrial Engineering,
Science and Research Branch, Islamic Azad University, Tehran, Iran

Received 27 April 2018
Revised 14 June 2018
Accepted 27 June 2018

Downloaded by 178.252.177.197 At 01:13 13 May 2019 (PT)

Abstract

Purpose – The purpose of this paper is to present an efficient model for project buffer sizing by taking failure mode and effects analysis (FMEA) into account to reach a more realistic schedule.

Design/methodology/approach – In the first phase of the project, several turbines were installed according to the primary schedule with an average duration of 142 days. Then, some of critical chain project management algorithms were separately applied in the implementation and installation of the other wind turbines. The adaptive procedure with resource tightness (APRT) method turned out to be the best method in terms of obtaining a more realistic schedule in this case study. Finally, FMEA was simultaneously applied with APRT.

Findings – Applying the hybrid method to the scheduling of the wind turbines, yielded the more realistic schedule than traditional.

Research limitations/implications – The proposed hybrid APRT-FMEA algorithm was implemented on a real wind farm construction project which was completed with 37 percent shorter duration than the initial estimation; in spite of the initial estimation of 142 days, the project completed in 103 days.

Practical implications – Introducing and implementing a new algorithm which is a combination of buffer sizing algorithms and one of the well-known and mostly used risk assessment methods in order to provide the more realistic project schedule in the construction of wind turbines.

Originality/value – Introducing and implementing a novel algorithm which is a combination of conventional buffer sizing method and one of the efficient risk assessment methods in order to make the schedule more realistic.

Keywords Optimization, Case study, Project management, Construction planning, Scheduling, Novel model

Paper type Research paper

1. Introduction

In most project scheduling problems with resource constraints, due to the scarcity of resources and equipment and the high level of expertise of some staff, it may not be possible to take advantage of any amount and number of them. For this reason, in the literature, all kinds of project scheduling problems have been presented with taking resource constraints into account. Nowadays, one of the major problems with projects is that they are not completed according to schedule. Nowadays the high level of competition in the market results in increasing the requests to complete the projects within the shortest possible time. This complicates the situation with considering resource constraints and uncertainty together, leading to delays and interruptions during the project execution. One way of increasing the reliability of the schedule is to create buffers by considering appropriate resources for performing activities in order to cope with deviations. For this purpose, a hybrid buffer sizing algorithm is presented in this paper based on a real case.

Project planning helps project construction achieve desired goals. Project planning involves envisioning the results which various organizations desire to acquire and determines the necessary steps for project success. In just a few years, applying wind

---

The authors are grateful to all of those with whom they have had the pleasure to work during this and other related projects.

Engineering, Construction and Architectural Management
© Emerald Publishing Limited
0969-9988
DOI 10.1108/ECAM-04-2018-0161

Downloaded by 178.252.177.197 At 01:13 13 May 2019 (PT)

energy around the world has matured dramatically and it is one of the fastest growing sources of electricity generation these days. Both development of wind energy technology and a decrease of wind power production cost have rapidly grown around the world in recent years (Deng *et al.*, 2011). Rozenes *et al.* (2006) maintained that the aim of project-control system is to minimize the gap between project planning and project execution in order to achieve the project objectives. Loring (2007) explored the dynamics of the planning process for wind energy in England, Wales and Denmark and studied the factors influencing project success. Planning is seen as important techniques in their own right as well as the components of more elaborate promotion programs incorporating multiple techniques (Eldredge *et al.*, 2016; Green and Kreuter, 1993). Zohrehvandi *et al.* (2017) presented a procedure for performing closing process group in a cycle power plant project. At the initial stages of planning, project management tries to ensure a successful outcome (Hu *et al.*, 2015). Zwikael (2009) investigated the relative importance of implementing project management knowledge areas during the project planning phase.

Critical chain project management (CCPM), proposed by Goldratt (1997), has proven to be a good methodology to schedule the resource-constrained projects during past decades. The application of CCPM has been proved to accomplish projects 10 to 50 percent faster and/or cheaper than the traditional methods (Goldratt, 1997; Leach, 2014; Newbold, 1998). Mansoorzadeh and Yusof (2011) suggested a reliable project scheduling approach, considering the integration of both risk management and critical chain schedule analysis. Ma *et al.* (2014) improved the CCPM framework to enhance the implementation of CCPM in construction project management practices. Pawiński and Sapiecha (2014) investigated cost-efficient project management based on critical chain method. Wang (2011) analyzed the concept of CCPM and rules of buffer in critical chain, and then put forward the methods and processes of designing critical chain project portfolio schedule. Robinson and Richards (2010) presented an overview of the aspects of critical chain that lead to success, and then provided an introduction to critical chain and its application.

Buffer management is one of the main features of the CCPM. Today, the Theory of Constraints (TOC) approach is supported by Goldratt Institute (Goldratt, 1994; Goldratt *et al.*, 2000; Goldratt and Cox, 2012). Buffers neither do protect individual tasks, nor belong to management. These buffers aggregate the protection which a project needs to meet its due date and allow focus on project duration (Leach, 1999). Tukel *et al.* (2006) introduced two methods to determine feeding buffer sizes in CCPM. Wang *et al.* (2010) proposed resource-constrained project scheduling problem as a key sub-problem in partner selection of multi-projects scheduling. Ma *et al.* (2012) offered an improved buffer sizing approach in critical chain scheduling based on the flexible management in projects. Zhang *et al.* (2011) introduced a new buffer sizing approach that considers the effect of various uncertainties in critical chain schedule. Zhang *et al.* (2017) developed a buffer sizing method based on a fuzzy resource-constrained project scheduling problem in order to obtain an appropriate proportionality between the activity duration and the buffer size.

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 procedure with density (APD) and adaptive procedure with resource tightness (APRT) (Ghoddousi *et al.*, 2017). Tukel *et al.* (2006) introduced APD and APRT methods for determining feeding buffer sizes in critical chain project schedule. Both methods were tested and compared with two RSEM and C&PM methods. The test results indicated that both of the suggested methods generated smaller buffer sizes while providing sufficient protection against delays in project completion time. In general, as RSEM does not consider the uncertainty and the dependence, the generated buffer size is not enough for either a high level of uncertainty or a high level of dependence. The APRT and APD algorithms take the uncertainty into account without

Downloaded by 178.252.177.197 At 01:13 13 May 2019 (PT)

considering the dependence (Bie *et al.*, 2012). Ghoddousi *et al.* (2017) studied a multi-attribute buffer sizing method aiming at maximizing the robustness of the buffered schedule generated (Ghoddousi *et al.*, 2017). Sobral *et al.* (2017) proposed a methodology to assess critical medical processes based on a FMEA technique, identifying and making a hierarchy of the inherent activities belonging to those processes using a quantified risk priority number (RPN). Neto *et al.* (2018) proposed a method for analysis of investment risks for wind power plants using innovative stochastic models to generate synthetic time series of wind speed and short-term price. Hallowell *et al.* (2018) quantified the risk of failure of offshore wind turbines to hurricane-induced wind and waves by developing and implementing a risk assessment framework that is adapted from a well-established framework in performance-based earthquake engineering. Presencia and Shafiee (2018) presented an evaluation and prioritization method for the collision risks associated with various kinds of ships used for carrying out maintenance tasks on different subassemblies of wind turbines in an offshore wind farm. Cheraghi *et al.* (2017) developed a mathematical programming model for selecting risk response strategies for construction projects. The model presented based on project iron triangle; time, cost and quality to obtain the optimal risk response strategy for the construction project. Ashley *et al.* (2017) applied FMEA in a social care context to evaluate the process for recognizing and referring children exposed to domestic abuse within one Midlands city safeguarding area in England.

Sovacool *et al.* (2017) investigated the risk of cost overruns and underruns occurring in the construction of 51 onshore and offshore wind farms commissioned between 2000 and 2015 in 13 countries. There is an indication that the risk increases for larger wind farms at greater distances offshore using new types of turbines and foundations. Loncar *et al.* (2017) examined the real options valuation of a potential onshore wind farm project in Serbia. The final binomial tree results show that the proposed sequence of options increases project value by transforming higher risk and lower return in the initial discounted cash flow model, to lower risk and higher return in the RO model. Gatzert and Kosub (2016) presented current risks and risk management solutions of renewable energy projects and to identify critical gaps in risk transfer, thereby differentiating between onshore and offshore wind parks with focus on the European market. Kucukali (2016) introduced a risk assessment tool to quantify economic, environmental, political and societal risks in wind energy projects. The risks are quantified based on the measured data and document evidence. Garcia and Bruschi (2016) provided a tool for improving proactive safety standards in onshore wind farms. The emergency management was outlined integrating some pinpointed indicators identified by wind turbines owners and manufacturers in a simple and practical instrument (risk assessment tool) aimed to facilitate emergency responses in case of accidents. Ashrafi *et al.* (2015) reviewed existing approaches of risk assessment for complex technological and specifically studies risk assessment of wind turbines. Shafiee (2015) proposed a fuzzy analytic network process approach, based on Chang's extent analysis, in order to select the "most appropriate risk mitigation strategy" for offshore wind farms.

Introducing and implementing a new algorithm which is a combination of buffer sizing algorithms and one of the well-known and mostly used risk assessment methods in order to provide the more realistic project schedule in the construction of wind turbines. In other words, by incorporating FMEA into conventional buffer sizing algorithms, especially APRT, the project schedule becomes more realistic. Further to our knowledge, there in previous study in the related literature. This paper aims to present an efficient algorithm for project buffer sizing by taking FMEA into account to reach a more realistic schedule. The results were obtained by applying this algorithm to a real-world construction project.

Downloaded by 178.252.177.197 At 01:13 13 May 2019 (PT)

2. Methodology

This paper introduces a new hybrid algorithm which is a combination of traditional buffer sizing algorithms and the widely used risk assessment method known as FMEA with the aim of making the more realistic project schedule. In the first phase of the project, several turbines (out of the total of 22 turbines) were installed according to the primary schedule with an average duration of 142 days. Then, the APD, APRT, RSEM and C&PM algorithms were separately applied in the implementation and installation of the other wind turbines, as fully explained in the sections case study of the article. The APRT method turned out to be the best method in terms of obtaining a more realistic schedule in this case study. However, this method had its own problems and constraints which were explained in the sections case study of the article. Therefore, to resolve these problems and constraints, FMEA was simultaneously applied with APRT. Applying the hybrid APRT-FMEA-method to the scheduling of one of the wind turbines, yielded the more realistic schedule than traditional. Therefore, this hybrid algorithm was applied to the implementation of the rest of the turbines. It is of note that all the 22 wind turbines in this project are alike with similar installation operations.

Concerning the possibility of arising a constraint such as the neutralization of the effects of the buffers in similar projects and spending extra time and finances on planning and implementing the projects, developing a new technique to predict similar constraints is deemed necessary. It is essential to note that the implementation of the APRT algorithm helps to identify the current bottlenecks of the project and eliminate them by taking buffers into consideration; however, it does not deal with preventing the probable bottlenecks or the neutralization of the effects of the safety margins or buffers in the future. It seems that a different technique should be used to decrease the probability of the occurrence of similar constraints. To achieve this aim, a tool used in the FMEA technique was applied because this tool is the most frequently used in production and project-oriented sites compared to the other risk-predicting tools. It is also more compatible with the procedure adopted in this research. By combining these two techniques, a new algorithm APRT-FMEA, which is an expanded version of APRT, is introduced. The following flowchart (Figure 1) illustrates the whole processes and steps of the research.

Hence, in this research, the APRT algorithm is implemented by considering safety margins, then, the FMEA technique is used to prevent the neutralization of the effects of the safety margins (buffers). No research has been conducted so far by combining the two APRT and FMEA methods, particularly applying to a real-world construction project as a case study, and this study is unique in this regard. By taking the risks and their potential impacts into account, a more realistic schedule was obtained. The proposed algorithm is explained in Figure 2.

3. Case study

MAPNA Group is a group of companies involved in construction and installation of energy generation machineries, including gas and steam turbines, wind turbines, heat recovery steam generators and conventional boilers, electrical generators, electrical and control systems and railway locomotives. The construction of the first wind farm began in 2012 and the project is still being executed to reach the total capacity of 100 MW. The total cost of the Kahak wind farm project, which includes 22 MB turbines, is about $5.5m.

As previously mentioned, the project is the first project in the Middle-East, in which 2.5 MW turbines are installed. The project was prolonged and lots of delays happened during the execution. As a result, it was found that the project could not be finished according to the initial schedule. The first turbine installation was completed in 142 days. The initial durations of the project activities were estimated by using the data gathered through interviews, which were conducted by different project experts and project managers (88 experts). First, the experts working on the sites of the wind farm construction projects, and the experts working in the central office have been identified. All of the experts had more than 15 years' experience

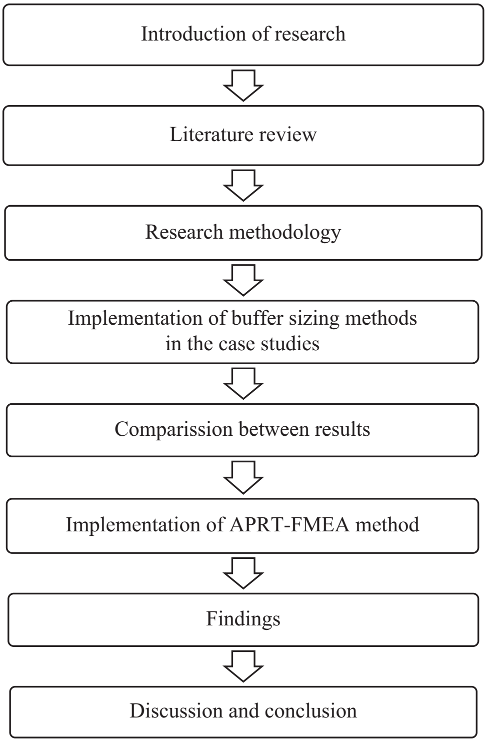

Figure 1.
Whole processes and steps of the research

Downloaded by 178.252.177.197 At 01:13 13 May 2019 (PT)

in planning, engineering, procurement and executing power plant construction projects with bachelor or master degree. The questions had been made and distributed to the experts before the interviews in order to be ready for responding to the questions effectively. The closed interviews have been conducted with the average duration of 40 min. The questions were mostly related to the types of activities, the durations of activities, the precedence relationship among activities and the required resources for the accomplishment of activities. The whole interview process took about six weeks. After data collection process, the data were analyzed and the initial schedule was prepared. Since this was the first wind farm construction project in Iran, there were no nationwide historical data. Hence, we inevitably used the information of the experts' judgments for data adjustment. The safe duration of construction and installation of a 2.5 MW wind turbine was initially estimated as 142 days. All activities for installation of one wind turbine are shown in Table I. These activities are the main tasks of the wind turbine construction project.

The justification for a single case lies in what Yin (1994) put forth. He maintained that using multiple cases should be investigated in distinct and multiple experiments and not in a single survey. He contended that the rationale behind this choice is that of replication not sampling. A wind farm construction project was selected as the case, given that a deep understanding of one case can provide universal information and insights that study of numerous cases cannot (Easton, 2010). Focusing on one case allows researchers to go back, study and review the case several times. Then, after exploration and reflection, they can examine their understanding of what they are studying (Easton, 2010). Flyvbjerg (2006) clarified that in conducting in-depth research on a topic, it is acceptable to study only one case, and the results can then be generalized. Strategic selection of the case can significantly

Downloaded by 178.252.177.197 At 01:13 13 May 2019 (PT)

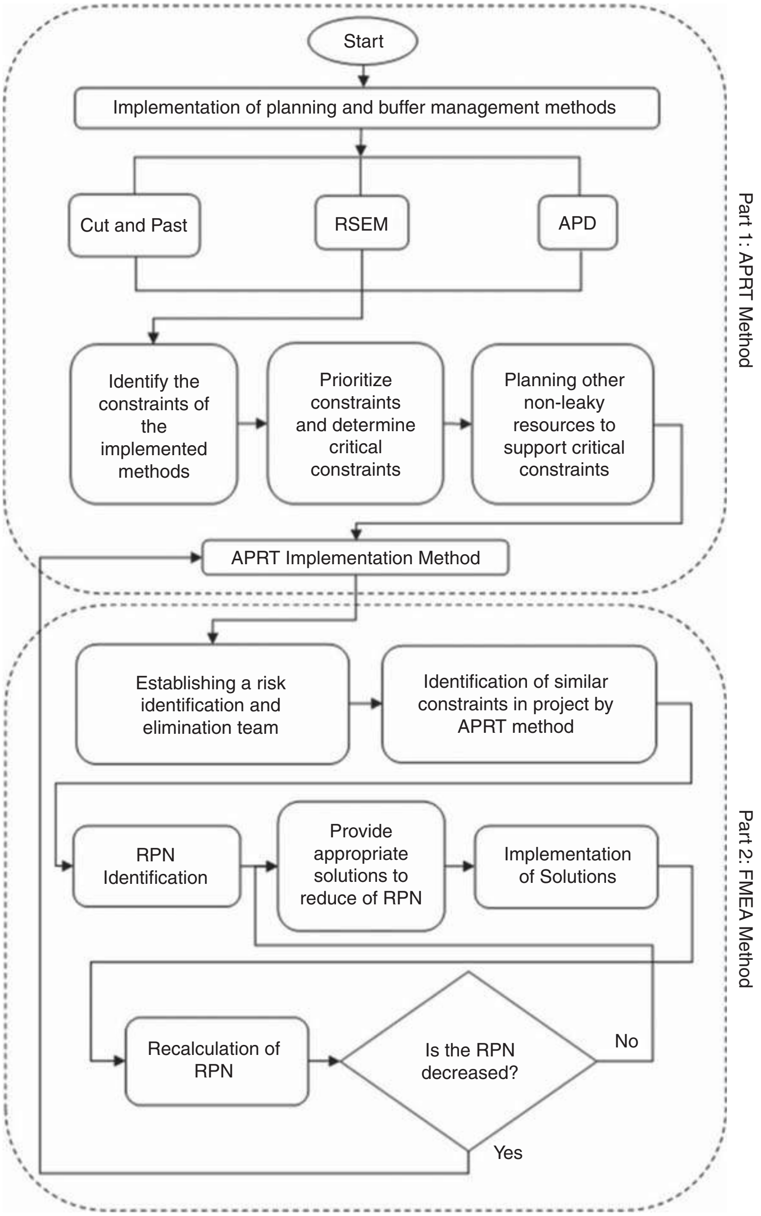

Figure 2.
Hybrid APRT-FMEA algorithm

increase the study's generalizability (Flyvbjerg, 2006). Accordingly, the wind farm construction project in this research was not chosen randomly. It was intended to select a specific construction project so as to obtain certain understandings that other construction projects would not be able to offer. As a result, to gain a deep understanding of the construction projects, wind farm projects in Iran that have so far not been executed were selected as a single case study.

Downloaded by 178.252.177.197 At 01:13 13 May 2019 (PT)

As previously mentioned, there are different methods for determining the buffer sizes that may be quite important for the project schedule. In this paper, we used the most common buffer sizing methods such as C&PM, RSEM, APRT and APD and subsequently compared the obtained results. The deviations of the activities are shown in Table II, which are the differences between the safe and aggressive durations (Vanhoucke, 2016). Aggressive durations were recalculated considering the resources and the network features, and were presented in Table II. These aggressive durations were determined on the basis of the type, quality and quantity of the resources, as well as the features of each task.

3.1 Cut and past method (C&PM)

In this method, after determining the critical chain of project, the durations of activities are halved, then the project buffer and feeding buffers are added to the chain of activities. These buffers aggregate the protection which a project needs to meet its due date and allow focus on project duration (Leach, 1999).

Figure 3 shows a critical chain schedule with buffers. In C&PM, task durations are estimated based on effort only. No allowance of time is made for any kind of interruptions or distractions. Each task is considered to have a 50 percent probability of completing on time. Safety, contingency and allowance for delays (stuff happening) are aggregated in buffers at the end of the project. Or, if multiple feeding chains exist, these allowances are aggregated at the end of each feeding chain. Buffers are sized at 50 percent of the length of the chains they protect.

In C&PM, buffers are often estimated at 50 percent of the "normal" activity duration (Wuliang *et al.*, 2013). Thus, the critical chain is about half the length of the critical path. According to Figure 3, after allocating the project buffer and feeding buffers and determining the critical chain, the time period of critical chain is obtained as 71 days, and the project buffer, which is the half of the critical chain, is considered as 35.5 days.

As depicted in Figure 3, in the last stage of updating, project progress was 100 percent, project buffers were entirely consumed by activities and the duration of the project critical chain reached to 113 days. In other words, 3.25 more days were consumed compared to the predetermined buffer. The project buffer and the feeding buffer were determined to be 35.5 days and 2 days, respectively. Furthermore, it took 113 days to implement a wind turbine using this method, and compared to the 142-day schedule, 29 days were saved.

Activities numbers	Activities name	Activities safe duration
1	Turbine foundation	95
2	Foundation of tubular tower	3
3	Preparation of installation	4
4	Installation electrical work	8
5	Assembly of towers	6
6	Assembly of the Nacelle and Rotor	14
7	Completion of the turbine	7
8	Final installation	2
9	Commissioning	28

Table I.
All activities for installation of one wind turbine

Activity	1	2	3	4	5	6	7	8	9
Safe duration	95	3	4	8	6	14	7	2	28
Aggressive duration	68	2	3	6	4	8	4	1	21

Table II.
Aggressive and safe activities duration

Downloaded by 178.252.177.197 At 01:13 13 May 2019 (PT)

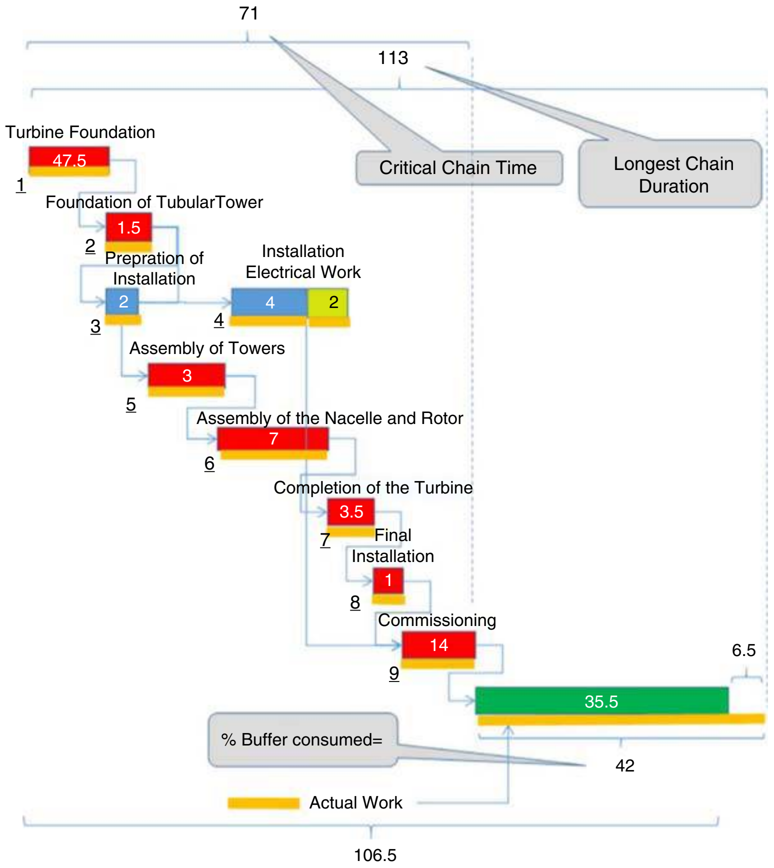

Figure 3.
Critical chain schedule with buffers in C&PM

3.2 *Root square error method (RSEM)*

Newbold (1998) developed the Goldratt's critical chain concepts and introduced another method:

$$[(S-A)12+(S-A)22+\ldots+(S-A)n2]1/2. \qquad (1)$$

According to Equation (1), for all n tasks on the path, where S, high confidence (safe) estimate and A, 50:50 (average) estimate. This method is often referred to as the sum of squares method, for it takes the sum of the squared differences between the low risk duration and the aggressive duration into account, leading to the following values:

$$\text{Project buffer} = 28.38$$

$$\text{Feeding buffer} = 2.62.$$

The project buffer was determined to be 28.38 days and the feeding buffer, 2.62 days. In addition, it took 110 days to implement a wind turbine, i.e., 32 days less than the 142-day schedule. The disadvantage of the RSEM is that it assumes that the project activities are independent without considering the interruptions imposed by external factors (Herroelen and Leus, 2001).

3.3 Adaptive procedure with density (APD)

Tukel *et al.* (2006) proposed the so-called APD method to determine feeding buffer sizes in CCPM. In this method, the buffer is sized as the standard deviation of the path leading to the buffer scaled by a factor which is calculated by taking the density of the subnetwork into account. The buffer size is determined according to the following equation:

$$\text{Buffer size} = K \times \sigma_{\text{path}}, \tag{2}$$

where K is the scaling factor based on the subnetwork density; σ_{path}, the standard deviation of the longest path feeding the buffer.

The standard deviation σ_{path} of a path is equal to the square root of the sum of the variances of the activities on that path:

$$\text{Critical chain } 1-2-5-6-7-8-9: \text{sqrt}(13+0.5+1+2.9+1.5+0.4+3.5) = 14,$$

$$\text{Feeding chain } 3-4: \text{sqrt}(0.7+1.1) = 1.3.$$

Equations (3), (4) and (5) were used to obtain K:

$$K = 1+\text{network density}. \tag{3}$$

Critical chain:

$$\text{Node}(n) = 7$$

$$\text{Potential connection(PC)} = (n \times (n-1))/2, \tag{4}$$

$$\text{PC} = 21$$

$$\text{Network density(ND)} = \text{actual connection/pc}, \tag{5}$$

$$\text{ND} = 0.29$$

$$K = 1+0.29 = 1.29$$

Feeding chain:

$$\text{Node}(n) = 2$$

$$\text{PC} = 21$$

$$\text{ND} = 1.00$$

$$K = 1+1.00 = 2.$$

The buffer sizes based on the APD are then equal to the following equation:

$$\text{Buffer} = K \times \text{Critical chain}. \tag{6}$$

$$\text{Project buffer} = 1.3 \times 14 = 18.24$$

$$\text{Feeding buffer} = 2 \times 1.3 = 2.62.$$

Downloaded by 178.252.177.197 At 01:13 13 May 2019 (PT)

Figure 4 illustrates the project and feeding buffers and subnetworks merging with their network density (ND) value in APD method.

The project buffer was calculated to be 18.24 days and the feeding buffer, 2.62 days. Besides, it took 109 days to implement a wind turbine, and as a result, 33 days were saved compared with the 142-day schedule.

3.4 Adaptive procedure with resource tightness (APRT)

Tukel *et al.* (2006) introduced the APRT which takes the scarceness or tightness of resources into account.

The buffer is sized as the standard deviation of the path leading to the buffer scaled by a factor which is calculated by considering the resource tightness. The buffer size is calculated according to the following equation:

$$\text{Buffer size} = K \times \sigma_{\text{path}}, \tag{7}$$

where K is the scaling factor based on the resource tightness; σ_{path}: the standard deviation of the longest path feeding the buffer.

The numbers below each node in Figure 4 refer to the aggressive activity durations while the label below the node refers to a renewable resource that is required to perform the activity. The renewable resources A, B, C and D have an availability of one. One project buffer is added to protect the critical chain S-1-2-5-6-7-8-9-E and one feeding buffer FB3-4 is added to protect the feeding chain 3-4, respectively.

The standard deviation of the longest path can be calculated in various ways. In this paper, it is assumed that the standard deviations of the activities are equal to 50 percent of the difference between the safe and aggressive durations according to Table II. The standard deviation σ_{path} of a path is then equal to the square root of the sum of the variances of the activities on that path, as follows:

$$\text{Critical chain } 1-2-5-6-7-8-9 : \text{sqrt}(13+0.5+1+2.9+1.5+0.4+3.5) = 14,$$

$$\text{Feeding chain } 3-4 : \text{sqrt}(0.7+1.1) = 1.3.$$

According to Table III, the resource tightness is a measure of the degree of resource use along the time horizon of all activities on the chain merging into the buffer. More precisely, it compares the total resource work content used by these activities with the total resource work content available during this time horizon for all resources. Total work content used

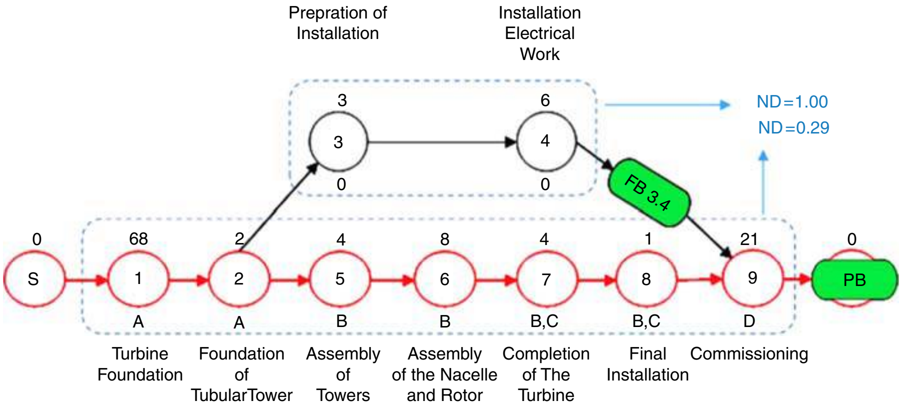

Figure 4.
Subnetworks merging

Downloaded by 178.252.177.197 At 01:13 13 May 2019 (PT)

by all activities on the chain is equal to the activity duration multiplied by the resource demand. The work content for activity 5 is equal to $4 \times 1 = 4$ for resource B. Total work content available along the length of the chain is equal to the duration of the longest path in the chain multiplied by the resource availability of the resource. This is equal to 101×2 for resource A of the critical chain.

The resource tightness is then calculated as the division of the two work contents, which leads to a value between 0 and 1, according to Equations (8), (9) and (10):

$$\text{Resource tightness} = \text{total work content used}/\text{total work content available}, \tag{8}$$

$$\text{Resource tightness for critical chain(RTCC)} = 1 + \text{Project buffer(PB)}, \tag{9}$$

$$\text{RTCC} = 1 + \text{PB}$$

$$\text{RTCC} = 1 + 0.21 = 1.22$$

$$\text{Resource tightness for feeding chain(RTFC)} = 1 + \text{Feeding buffer(FB)}, \tag{10}$$

$$\text{RTFC} = 1 + \text{FB}$$

$$\text{RTFC} = 1 + 0.67 = 1.7$$

The buffer sizes based on the APRT method are then equal to the following equations:

$$\text{PB} = \text{Critical chain} \times \text{RTCC}, \tag{11}$$

$$\text{PB} = 14 \times 1.22 = 17.25$$

$$\text{FB} = \text{Feeding chain} \times \text{RTFC}, \tag{12}$$

$$\text{FB} = 1.3 \times 1.7 = 2.22.$$

The project buffer turned out to be 17.25 days and the feeding buffer, 2.22 days. Using this method also resulted in finishing a wind turbine in 107 days, 35 days earlier than the 142-day schedule.

3.5 Implementation of hybrid APRT-FMEA algorithm

There may be many simultaneous constraints in an organization, but only one of them would be detected, examined and removed as the main constraint. Here we want to reach a state where the constraint to be examined and removed in the organization is a new and unrepeated one. To this end, one of the risk assessment techniques ought to be used.

Resource	Average resource for project buffer	Average resource for feeding buffer 3-4
A	0.21	0.33
B	0.05	0.33
C	0.03	0.67
D	0.18	–
Maximum	0.21	0.67

Table III. Average resource to calculate the resource tightness

Downloaded by 178.252.177.197 At 01:13 13 May 2019 (PT)

There are many ways to predict the risks in an organization, each with several strengths and weaknesses. However, for the sake of this research, due to the fact that the points under examination are inherently project-oriented, the FMEA was applied.

In this research, attempts have been made to detect and remove the constraints. Now, we want to identify and remove similar constraints in the future using a precise and practical procedure. The algorithm applied in this procedure is depicted in Figure 5.

Detection and prediction of the constraints of the organization for the first time should be carried out by a team of experts fully familiar with the principles of TOC, because there is not a centralized data bank of the constraints of the organization.

Constraints are of three types:

1. repeated and predictable constraints;
2. unexpected and predictable constraints; and
3. unexpected and unpredictable constraints.

The goal of using this procedure is to remove type one constraints and reduce the probability of type two constraints and also make an effort to decrease type three constraints and turning them into type two constraints.

3.5.1 Risk priority number (RPN) in FMEA table. According to Equation (13), the RPN is the mathematical product of the three criteria: severity number, occurrence number and detection number:

$$\mathrm{RPN} = D \times S \times O. \tag{13}$$

The RPN may lead the team to constraints which are not of much importance to the organization; however, in a multitude of executive procedures, the following two provisos have been introduced as complements to the RPN:

- prioritizing the failures with a severity number equal to or greater than 9 and examining these failures for the sake of prediction; and

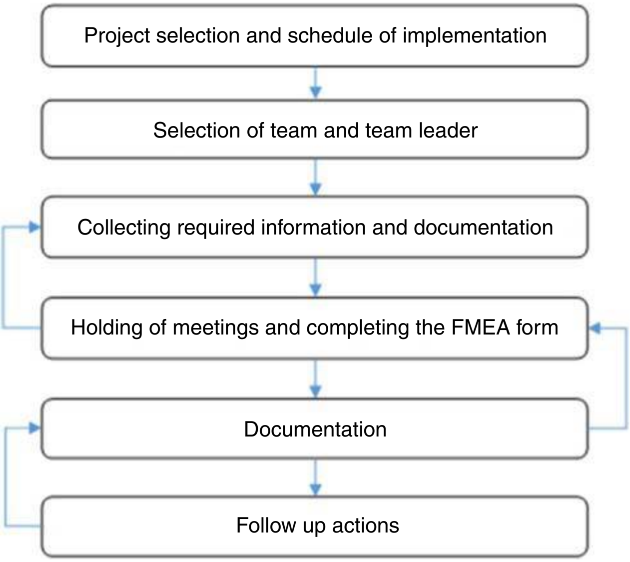

Figure 5.
Execution algorithm of FMEA

Downloaded by 178.252.177.197 At 01:13 13 May 2019 (PT)

Downloaded by 178.252.177.197 At 01:13 13 May 2019 (PT)

- failures with high occurrence and severity have to be noted and considered for proposed measures.

Figure 6 is the research conceptual model and shows variables under examination in the form of a conceptual model with an explanation of studying and measuring the variables.

Potential constraints:

1. The constraint of inability to estimate the project's actual duration after using APRT model several times (from now on in this research, this constraint will be referred to as the first constraint of the model).

   It is not very easy to request a time estimate of the activities from people according to the hybrid APRT-FMEA algorithm. Furthermore, they will hardly accept a reduction in their estimates. Nevertheless, if a manager can ever reduce their estimate, they may give exaggerated estimates in order to preserve their desirable safety margin after the likely reduction in their estimates:

   - Solution: building a team of experts to determine a time schedule for project planning and supervise the executive teams on a regular basis in order to encourage them to make progress based on the schedule.

2. The constraint of slackness and laziness of the experts in all parts of the project:

   - Solution: establishing a time and work assessment system and providing time standards for all activities and handing them out to the managers; providing a timetable for giving output reports as a basis for a regular and periodic supervision.

Table IV shows the calculations in regards the initial RPN.

3.5.2 Implementation of hybrid APRT-FMEA algorithm after calculation of the initial RPN. To achieve this goal, the problem-solving technique in the TOC is used; to wit, all proposed solutions are not dealt with simultaneously; instead, the constraints are first prioritized based on their RPN and then, they are removed according to the proposed solutions; that is to say, the likelihood of their occurrence decreases. In order to do that, the following steps were taken:

1. The constraint of inability to estimate the project's actual duration after using APRT model several times.

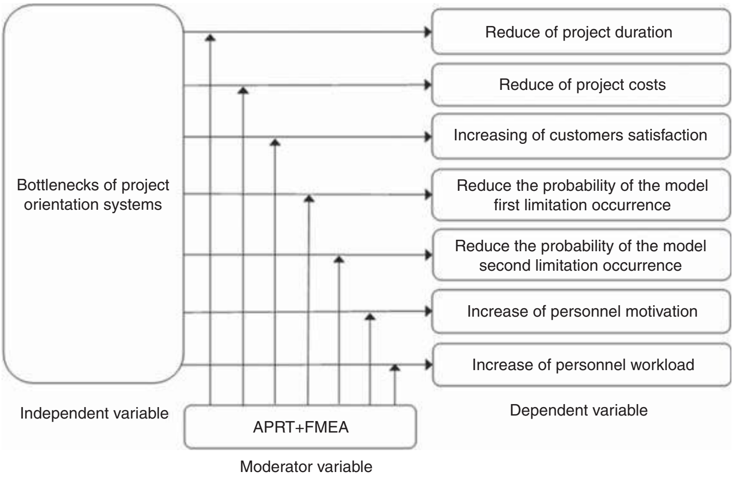

Figure 6.
Research conceptual model

Downloaded by 178.252.177.197 At 01:13 13 May 2019 (PT)

Table IV.
Calculating the initial RPN

Unit	Executive teams	Executive teams
Potential constraint	Inability to estimate the project actual duration	Slackness and laziness of the experts
Potential effects of the constraint	Excessive lengthening of the project duration, high final costs, inability to give a due date to the customer	The activities not only will not finish according to the CCPM timetable, but they also go beyond it
Severity	8	6
Potential causes of the constraint	The student's syndrome, Parkinson's law, and giving an exaggerated duration by the managers	Student's syndrome, Parkinson's law, Murphy's law
Occurrence	9	8
Detection	5	2
Proposed measure	Building a team of experts to provide a time schedule for project planning and supervise the executive teams on a regular basis	Establishing a time and work assessment system and providing time standards for all activities and giving them to the managers; providing a timetable for giving output reports for a regular and periodic supervision
RPN	360	96

This constraint is the main and the most important one considering its RPN. In order to remove this constraint, a team of experts should be built to determine a time schedule for project planning and supervise the executive teams on a regular basis in order to encourage them to make progress in accordance with the time schedule. To achieve this aim, the required preliminaries were prepared as follows:

- building a team of skilled and committed experts out of all the company's teams;
- creating a schedule for the expert team for inspection and supervision;
- allocating a budget for encouraging tidy and successful teams;
- establishing a work assessment system; and
- hiring some people to strengthen the project-control and work assessment units.

(2) The constraint of slackness and laziness of the experts.

Considering the fact that the obtained RPN is 96 in the table, the above-mentioned constraint is ranked second among the risks. To remove this constraint, a time and work assessment system need to be implemented and a time standard for each activity be given to the managers. It is also essential to provide a timetable for giving output reports as a basis for a regular and periodic supervision with the aim of preventing this constraint. To achieve this goal, the following measures were taken:

- Making daily work assessment sheets.

  Special sheets were designed to assess the personnel's daily work. Each individual was required to give the sheet to their respective manager at the end of the workday. Each individual's daily work and activities are well specified on these sheets:

- Creating a work and time assessment system.

  It is deemed essential to create a work and time assessment system in order to standardize the activity duration and an individual's work. To achieve this goal, after the removal of the first constraint, several individuals with differing levels of expertise were chosen as a sample and the time spent by each person on each activity was measured and in turn, the average time required to perform each activity was specified. Considering the fact that the amount of time required to perform each activity is determined by the experts, this constraint can be prevented by comparing the individuals' performance assessment sheets with the standards defined by the experts.

After the implementation of the proposed solutions presented in the initial table of FMEA feasible in the time span of this research, Table V was confirmed by the expert team.

3.5.3 The analysis of the results of using FMEA model. After comparing the FMEA tables before and after the execution of the proposed measures, the following results were obtained:

1. The constraint of inability to estimate the project's actual duration after using APRT several times.

   After implementing the proposed measures to remove this constraint, the RPN decreased from 360 to 32 because after taking the above-mentioned measures, the likelihood of the occurrence of the constraint has sharply decreased and its detection and prevention in the future becomes easier too, so that as soon as the conditions of the occurrence of this constraint emerge, the system detects the risk and will easily control it.

2. The constraint of experts' slackness.

   The RPN regarding this constraint decreased from 96 to 24. As can be seen, severity has not changed; however, the likelihood of the occurrence and detection of this constraint in the future decreased by half.

   In conclusion, after calculating the new RPNs, it was revealed that the previous constraints had been removed and the probability of their occurrence in the future was insignificant. At this stage, measures should be taken to identify and detect new constraints in the company, and this continual improvement process should be followed. The amounts of the project buffer and the feeding buffer were similar to those obtained in APRT; however, the time required to implement a wind turbine decreased to 103 days, 39 days earlier than the 142-day schedule.

4. Findings

In line with the results of implementing the hybrid APRT-FMEA algorithm in this case study, Figure 7 shows a critical chain schedule with buffers. The CCPM identifies the longest chain of both precedence and resource-dependent tasks in the generated project schedule as the critical chain of project network schedule (Goldratt, 1997). Note that buffers

Unit	Executive teams	Executive teams
Potential constraint	Inability to estimate the project actual duration	Slackness and laziness of the experts
Potential effects of the constraint	Excessive lengthening of the project duration, high final costs, inability to give a due date to the customer	The activities not only will not finish according to the CCPM timetable, but they also go beyond it
Severity	8	6
Potential causes of the constraint	The student's syndrome, Parkinson's law, and giving an exaggerated duration by the managers	Student's syndrome, Parkinson's law, Murphy's law
Occurrence	4	4
Detection	1	1
Proposed measure	Building a team of experts to provide a time schedule for project planning and supervise the executive teams on a regular basis	Establishing a time and work assessment system and providing time standards for all activities and giving them to the managers; providing a timetable for giving output reports for a regular and periodic supervision
RPN	32	24

Table V.
Recalculation of RPN

Downloaded by 178.252.177.197 At 01:13 13 May 2019 (PT)

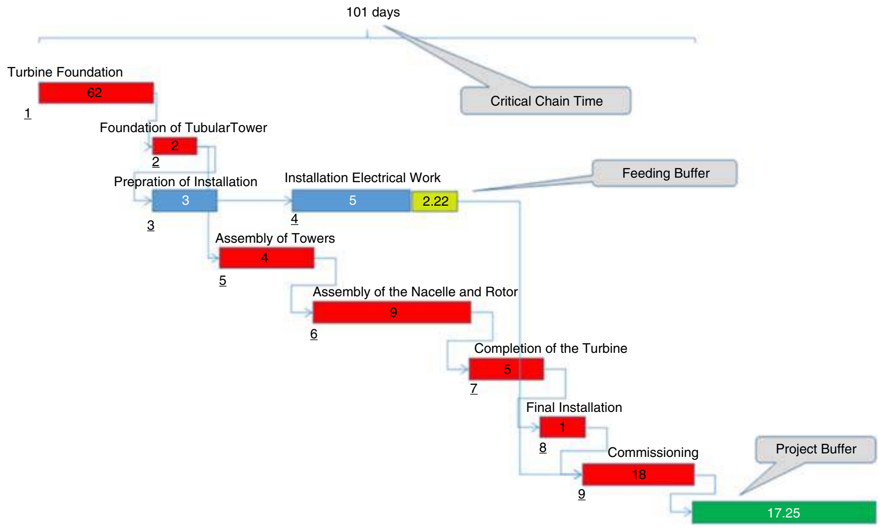

Figure 7.
Critical chain schedule with

Downloaded by 178.252.177.197 At 01:13 13 May 2019 (PT)

do not protect individual tasks. Buffers do not belong to management. Buffers can be used by any task and they exist to protect the total project commitment.

According to Figure 7, after allocating the project buffer and feeding buffers and determining the critical chain, the time period of critical chain is obtained as 101 days, and the project buffer is calculated as 17.25 days. Also, the duration of the feeding buffer is calculated as 2.22 days. Having launched the project, the planning and project-control unit regularly update the project activities. After the start of the project, the information of project buffer fluctuations was updated, measured and recorded in 10-day intervals. As depicted in Figure 8, at the last stage of updating and recording the project buffer fluctuations, project progress was 100 percent, 2 days of project buffer were consumed by activities, and the duration of the project critical chain reached 103 days. At this stage, 9.4 percent of the project buffer was consumed.

This critical ratio, or buffer burn rate, forms the foundation stone of managing uncertainty. The critical ratio provides a clear and objective measurement system to determine which resources subordinate to what on any given day.

As depicted in Figure 8, the critical ratio can be mapped daily on a trend (or fever) chart. Ideally, the critical ratio should trend within the area of the trend chart shaded yellow, meaning that work on the longest chain is being completed at a commensurate rate with consumption of the project buffer.

Table VI shows all buffer fluctuations and the condition of the project resource allocation, from the project beginning to its end. In this table, the duration of critical chain has boosted from 101 to 103 days.

Regarding the project buffer consumed (PBC) calculations and the longest chain completed (LCC) in Table VI, which is obtained from the project beginning to the end, it is shown in Figure 9 the buffer conditions are in the highest zone of green region, below the yellow region over the entire project duration, which shows that adequate resources have been allocated to the project.

Each of these zones is associated with an instruction:

(1) green: do nothing (your intervention is likely to do harm);

(2) amber: observe and plan, but do not intervene; and

(3) red: intervene, and take steps to expedite the project out of the red zone.

Downloaded by 178.252.177.197 At 01:13 13 May 2019 (PT)

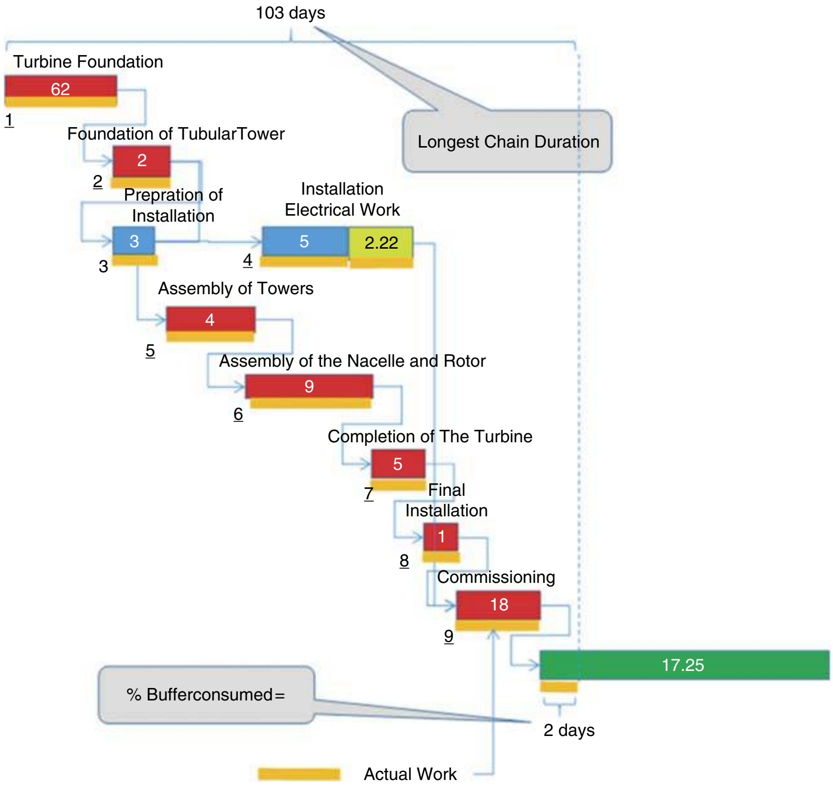

Figure 8.
Critical chain schedule with buffers in hybrid

Table VI.
All buffer fluctuations

Days	Longest chain duration	Longest chain completed (LCC)	Project buffer consumed (PBC)	Critical ratio (LCC/PBC)
5	101.0	4.95	0.0	10.54
15	101.1	14.84	0.3	4.52
25	101.2	24.72	0.7	3.51
35	101.2	34.58	0.9	3.68
45	101.4	44.38	1.9	2.36
55	101.5	54.19	2.3	2.31
65	101.8	63.85	3.8	1.70
75	102.1	73.46	5.2	1.42
85	102.4	83.01	6.6	1.26
95	102.7	92.50	8.0	1.16
103	103.0	100.00	9.4	1.07

These instructions enable the project manager to direct his limited capacity to where it will produce the greatest overall benefit. Buffer penetration also provides the project manager with valuable feedback for planning future projects. According to the obtained results, it can be inferred that using hybrid APRT-FMEA algorithm in the planning and control processes of the project leads to completing the project with 37 percent less duration than the initial estimation; in spite of the initial estimation of 142 days, the project completed in 103 days.

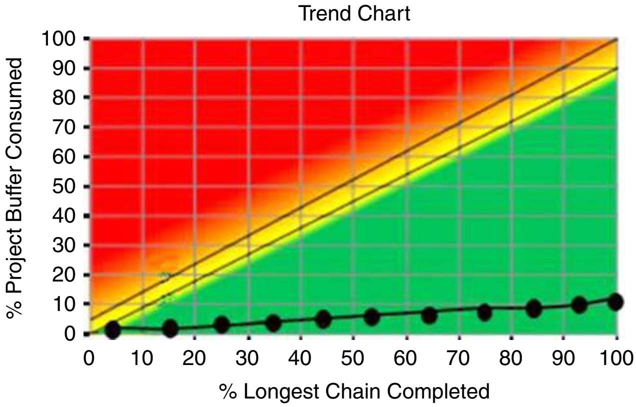

Figure 9.
All buffer penetrations and action decisions

Downloaded by 178.252.177.197 At 01:13 13 May 2019 (PT)

The results of scheduling and buffer sizing methods implementation in the project are shown in Table VII.

The obtained results for the project buffer, the actual duration and the feeding buffer when applying APD, RSEM, C&PM, APRT and hybrid APRT-FMEA algorithm.

5. Discussion and conclusion

This paper introduced a new hybrid algorithm which was a combination of traditional buffer sizing algorithms and the widely used risk assessment method known as FMEA with the aim of making the more realistic project schedule. In the first phase of the project, several turbines (out of the total of 22 turbines) were installed according to the primary schedule with an average duration of 142 days. Then, the APD, APRT, RSEM and C&PM algorithms were separately applied in the implementation and installation of the other wind turbines. The APRT method turned out to be the best method in terms of obtaining a more realistic schedule in this case study. However, this method had its own problems and constraints. Therefore, to resolve these problems and constraints, FMEA was incorporated into APRT. Applying the hybrid APRT-FMEA-method to the scheduling of one of the wind turbines, yielded the more realistic schedule than traditional. Therefore, this hybrid algorithm was applied to the implementation of the rest of the turbines. It should be noted that all the 22 wind turbines in this project are alike with similar installation operations.

This case study was conducted in the wind farm construction project which is the first wind farm in Mega Watt class in Iran and the Middle-East. In this research, we inevitably used the information of experts' judgments for data adjustment. Introducing and implementing a novel algorithm which is a combination of conventional buffer sizing method and one of the efficient risk assessment methods in order to make the schedule more realistic. In other words, by integrating FMEA with buffer sizing algorithms, especially APRT, the project schedule becomes more realistic.

Table VII.
Results of scheduling and buffer sizing methods implementation

Methods	C&PM	RSEM	APD	APRT	Hybrid APRT-FMEA algorithm
Safe duration	142	142	142	142	142
Actual duration	113	110	109	107	103
Variance	29	32	33	35	39
Project buffer	35.50	28.38	18.24	17.25	17.25
Feeding buffer	2.00	2.62	2.62	2.22	2.22

Concerning the possibility of arising a constraint such as neutralization of the effect of the buffers on similar projects and spending extra time and finances on planning and implementing the projects, developing a new model to predict similar constraints is deemed necessary. It is essential to note that the implementation of the APRT algorithm helps to identify the current bottlenecks of the project and eliminate them by taking buffers into consideration; however, it does not deal with preventing the probable bottlenecks or the neutralization of the effects of the safety margins or buffers in the future. It seemed that a different technique should be used to decrease the probability of the occurrence of similar constraints. For this purpose, the FMEA technique was applied. Therefore, by combining these two techniques, a new algorithm (hybrid APRT-FMEA algorithm), which is an expanded version of APRT, was introduced.

As explained before, the results were obtained by the implementation of the proposed algorithm on a real construction project. A turbine construction in the project was completed sooner than it had been scheduled. After implementation of the hybrid APRT-FMEA algorithm, the project was completed with 37 percent shorter duration than the initial estimation; in spite of the initial estimation of 142 days, the project completed in 103 days. Taking the resources and risks into account in the project's schedule will result in timely completion of the projects (Guo *et al.*, 2017). This model was applied through a case study of constructing wind farm turbines with successful results. This model can therefore be used in similar projects as well as other projects and reach more realistic schedule. With the application of FMEA in buffer sizing algorithms, a more realistic schedule was obtained by considering the risks and their potential impacts in project scheduling.

This paper motivates future research in wind farm construction projects. This paper can be useful for academic researchers, project managers and practitioners, and professionals who contribute to the wind farm construction projects. Extensive surveys can be conducted in other real-world wind farm projects in different countries to further compare, test and verify these algorithms and might be useful to extend the proposed model by the incorporation of the fuzzy method. Also, the other risk analysis methods could be applied and compared in various wind farm projects in different countries. It is suggested to apply the proposed method to other projects in different industries, and various countries and compare the results. In addition, details about the impact of this research on social and economic benefits could be analyzed. In addition, for different countries and regions, the standards and construction processes may also be different. Therefore, it is also a good idea to investigate how to upgrade this method for different requirements.

5.1 Data availability statement

Data gathered and analyzed during the study are available from the corresponding author by request.

Downloaded by 178.252.177.197 At 01:13 13 May 2019 (PT)

References

Ashley, L., Armitage, G. and Taylor, J. (2017), "Recognising and referring children exposed to domestic abuse: a multi-professional, proactive systems-based evaluation using a modified Failure Mode and Effects Analysis (FMEA)", *Health & Social Care in the Community*, Vol. 25 No. 2, pp. 690-699.

Ashrafi, M., Davoudpour, H. and Khodakarami, V. (2015), "Risk assessment of wind turbines: transition from pure mechanistic paradigm to modern complexity paradigm", *Renewable and Sustainable Energy Reviews*, Vol. 51 No. 1, pp. 347-355.

Downloaded by 178.252.177.197 At 01:13 13 May 2019 (PT)

Bie, L., Cui, N. and Zhang, X. (2012), "Buffer sizing approach with dependence assumption between activities in critical chain scheduling", *International Journal of Production Research*, Vol. 50 No. 24, pp. 7343-7356.

Cheraghi, E., Khalilzadeh, M., Shojaei, S. and Zohrehvandi, S. (2017), "A mathematical model to select the risk response strategies of the construction projects: case study of Saba tower", *Procedia Computer Science*, Vol. 121 No. 1, pp. 609-616.

Deng, Y., Yu, Z. and Liu, S. (2011), "A review on scale and siting of wind farms in China", *Wind Energy*, Vol. 14 No. 3, pp. 463-470.

Easton, G. (2010), "Critical realism in case study research", *Industrial Marketing Management*, Vol. 39 No. 1, pp. 118-128.

Eldredge, L.K.B., Markham, C.M., Kok, G., Ruiter, R.A. and Parcel, G.S. (2016), *Planning Health Promotion Programs: An Intervention Mapping Approach*, John Wiley & Sons, Hoboken, NJ.

Flyvbjerg, B. (2006), "Five misunderstandings about case-study research", *Qualitative Inquiry*, Vol. 12 No. 2, pp. 219-245.

Garcia, D.A. and Bruschi, D. (2016), "A risk assessment tool for improving safety standards and emergency management in Italian onshore wind farms", *Sustainable Energy Technologies and Assessments*, Vol. 18 No. 1, pp. 48-58.

Gatzert, N. and Kosub, T. (2016), "Risks and risk management of renewable energy projects: the case of onshore and offshore wind parks", *Renewable and Sustainable Energy Reviews*, Vol. 60 No. 1, pp. 982-998.

Ghoddousi, P., Ansari, R. and Makui, A. (2017), "A risk-oriented buffer allocation model based on critical chain project management", *KSCE Journal of Civil Engineering*, Vol. 21 No. 5, pp. 1536-1548.

Goldratt, E.M. (1994), *It's not Luck*, North River Pr, MA.

Goldratt, E.M. (1997), *Critical Chain: A Business Novel*, North River Press, Great Barrington, MA.

Goldratt, E.M. and Cox, J. (2012), *The Goal: A Process of Ongoing Improvement (25 Anv Rev.)*, North River Pr, MA.

Goldratt, E.M., Schragenheim, E. and Ptak, C. (2000), Necessária, sim, mas não suficiente: uma história baseada na Teoria das Restrições, North River Press, Great Barrington, MA.

Green, L.W. and Kreuter, M.W. (1993), *Health Promotion Planning: An Educational and Ecological Approach*, McGraw-Hill, New York, NY.

Guo, S.J., Chen, J.H. and Chiu, C.H. (2017), "Fuzzy duration forecast model for wind turbine construction project subject to the impact of wind uncertainty", *Automation in Construction*, Vol. 81 No. 1, pp. 401-410.

Hallowell, S.T., Myers, A.T., Arwade, S.R., Pang, W., Rawal, P., Hines, E.M., Hajjar, J.F., Qiao, C., Valamanesh, V., Wei, K. and Carswell, W. (2018), "Hurricane risk assessment of offshore wind turbines", *Renewable Energy*, Vol. 125 No. 1, pp. 234-249.

Herroelen, W. and Leus, R. (2001), "On the merits and pitfalls of critical chain scheduling", *Journal of Operations Management*, Vol. 19 No. 5, pp. 559-577.

Hu, X., Cui, N. and Demeulemeester, E. (2015), "Effective expediting to improve project due date and cost performance through buffer management", *International Journal of Production Research*, Vol. 53 No. 5, pp. 1460-1471.

Kucukali, S. (2016), "Risk scorecard concept in wind energy projects: an integrated approach", *Renewable and Sustainable Energy Reviews*, Vol. 56 No. 1, pp. 975-987.

Leach, L.P. (1999), "Critical chain project management improves project performance", *Project Management Journal*, Vol. 30 No. 2, pp. 39-51.

Leach, L.P. (2014), *Critical Chain Project Management*, Artech House, London.

Loncar, D., Milovanovic, I., Rakic, B. and Radjenovic, T. (2017), "Compound real options valuation of renewable energy projects: the case of a wind farm in Serbia", *Renewable and Sustainable Energy Reviews*, Vol. 75 No. 1, pp. 354-367.

Loring, J.M. (2007), "Wind energy planning in England, Wales and Denmark: factors influencing project success", *Energy Policy*, Vol. 35 No. 4, pp. 2648-2660.

Ma, G., Li, L. and Chen, Z. (2012), "Research on the buffer sizing approach in critical chain scheduling in perspective of flexible management", in Zhu, M. (Ed.), *Business, Economics, Financial Sciences, and Management*, Springer, Berlin and Heidelberg, pp. 61-68.

Ma, G., Wang, A., Li, N., Gu, L. and Ai, Q. (2014), "Improved critical chain project management framework for scheduling construction projects", *Journal of Construction Engineering and Management*, Vol. 140 No. 12, pp. 1-12.

Mansoorzadeh, S. and Yusof, S.R.M. (2011), "Reliable project scheduling with combination of risk management and critical chain schedule", *2011 IEEE Student Conference on Research and Development (SCOReD)*, pp. 442-447.

Neto, D.P., Domingues, E.G., Calixto, W.P. and Alves, A.J. (2018), "Methodology of investment risk analysis for wind power plants in the Brazilian free market", *Electric Power Components and Systems*, Vol. 46 No. 3, pp. 316-330.

Newbold, R.C. (1998), *Project Management in the Fast Lane: Applying the Theory of Constraints*, CRC Press, FL.

Pawiński, G. and Sapiecha, K. (2014), "Cost-efficient project management based on critical chain method with partial availability of resources", *Control and Cybernetics*, Vol. 43 No. 1, pp. 95-109.

Presencia, C.E. and Shafiee, M. (2018), "Risk analysis of maintenance ship collisions with offshore wind turbines", *International Journal of Sustainable Energy*, Vol. 37 No. 6, pp. 576-596.

Robinson, H. and Richards, R. (2010), "Critical chain project management: motivation & overview", *2010 IEEE Aerospace Conference*, pp. 1-10.

Rozenes, S., Vitner, G. and Spraggett, S. (2006), "Project control: literature review", *Project Management Journal*, Vol. 37 No. 4, pp. 5-14.

Shafiee, M. (2015), "A fuzzy analytic network process model to mitigate the risks associated with offshore wind farms", *Expert Systems with Applications*, Vol. 42 No. 4, pp. 2143-2152.

Sobral, J., Teixeira, D., Morais, H. and Neves, M. (2017), "Methodology to assess medical processes based on a Failure Mode and Effects Analysis (FMEA)", *2017 IEEE 5th Portuguese Meeting on Bioengineering (ENBENG)*, pp. 1-4.

Sovacool, B.K., Enevoldsen, P., Koch, C. and Barthelmie, R.J. (2017), "Cost performance and risk in the construction of offshore and onshore wind farms", *Wind Energy*, Vol. 20 No. 5, pp. 891-908.

Tukel, O.I., Rom, W.O. and Eksioglu, S.D. (2006), "An investigation of buffer sizing techniques in critical chain scheduling", *European Journal of Operational Research*, Vol. 172 No. 2, pp. 401-416.

Vanhoucke, M. (2016), *Integrated Project Management Sourcebook*, Springer International Publishing, Basel.

Wang, X., Bai, Y., Cai, C. and Yan, X. (2010), "Application of resource-constrained project scheduling with a critical chain method on organizational project management", *2010 International Conference on Computer Design and Applications (ICCDA)*, Vol. 2, pp. V2-V51.

Wang, Y. (2011), "Study on critical chain project portfolio management", *2011 International Conference on Management and Service Science (MASS)*, pp. 1-4.

Wuliang, P., Hui, S. and Yongping, H. (2013), "A genetic algorithm for the critical chain project scheduling problem", *International Journal of Digital Content Technology and its Applications*, Vol. 7 No. 3, pp. 571-578.

Yin, R.K. (1994), *Case Study Research – Design and Methods*, 2nd ed., Applied Socia Research Methods Series, Vol. 5, Sage, Newbury Park, CA.

Zhang, J., Song, X. and Díaz, E. (2017), "Critical chain project buffer sizing based on resource constraints", *International Journal of Production Research*, Vol. 55 No. 3, pp. 671-683.

Downloaded by 178.252.177.197 At 01:13 13 May 2019 (PT)