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ORIGINAL RESEARCH

PROBABILISTIC SCHEDULING BASED ON HYBRID BAYESIAN NETWORK–PROGRAM EVALUATION REVIEW TECHNIQUE

Tri Joko Wahyu Adi* | Farida Rachmawati | Safira Yulia Rizky

Dept. of Civil Engineering, Institut Teknologi Sepuluh Nopember, Surabaya, Indonesia

Correspondence

*Tri Joko Wahyu Adi, Dept of Civil Engineering, Institut Teknologi Sepuluh Nopember, Surabaya, Indonesia. Email: trijokowahyuadi@gmail.com

Present Address

Gedung Teknik Sipil, Jl. Taman Alumni, Surabaya 60111, Indonesia

Abstract

Project scheduling based on probabilistic methods commonly uses the Program Evaluation Review Technique (PERT). However, practitioners do not widely utilize PERT-based scheduling due to the difficulty in obtaining historical data for similar projects. PERT has several drawbacks, such as the inability to update activity durations in real time. In reality, changes in project conditions related to resources have a highly dynamic nature. The availability of materials, fluctuating labor productivity, and equipment significantly determine the project completion time. This research aims to propose a probabilistic scheduling model based on the Hybrid Bayesian Network-PERT. This model combines PERT with Bayesian Network (BN). BN is used to accommodate real-time changes in resource conditions. The modeling of BN diagrams and variables is obtained through an in-depth literature review, direct field observations, and distributing questionnaires to experts in project scheduling. The model is validated by applying the proposed model to a 60 m concrete bridge construction project in Indonesia. The simulation results of the proposed model are then compared with the case study project to assess the model's accuracy. The result of the study shows that the proposed hybrid Bayesian-PERT model is accurate and can eliminate the weaknesses of the PERT method. Besides being able to provide an accurate prediction of project completion time (93.4%), this model can also be updated in real-time according to the actual condition of the project.

KEYWORDS:

Bayesian Network, Construction Risk, PERT, Productivity, Project Scheduling

1 | INTRODUCTION

Probabilistic project scheduling is crucial in project management due to the dynamic and risky nature of projects. In traditional project scheduling, the time required to complete tasks or activities is assumed to be constant, thus not taking into account the possibility of delays or changes in the execution time due to the risk of resource constraints, including materials, labor, and equipment. In probabilistic scheduling, project activities are estimated with different probabilities, considering the likelihood of delays or changes in the execution time. This approach helps project managers create more realistic plans and provides more accurate results regarding project completion time[1].

The PERT (Program Evaluation and Review Technique) method is a commonly used probabilistic project scheduling method in project management[2]. This method takes into account the uncertainties and risks associated with a project to determine a realistic and accurate schedule. In the PERT method, project activities are predicted using three different time estimates: the optimistic time, the pessimistic time, and the most likely time. From these three-time estimates, PERT calculates the average time required to complete each activity. The PERT method also utilizes a network of activities to illustrate the relationships between activities in the project. By using the activity network and the calculated time estimates, PERT can calculate the probability of the total time required to complete the entire project and identify critical activities.

Although the PERT method has many advantages, it also has several drawbacks. These include: The PERT method requires more time and cost in planning and implementation, as it necessitates accurate data collection and longer analysis time[3]. While PERT considers uncertainty in project scheduling, the time estimates are based solely on historical data from similar projects. However, each project has unique and varying conditions, resulting in less realistic schedules. The PERT method only considers quantitative factors in project scheduling, such as time and cost, while neglecting qualitative factors like material delay, construction labor, and equipment productivity. PERT does not consider limited project resources, such as the availability of labor, raw materials, or equipment, which can lead to unrealistic scheduling. PERT is unable to handle real-time changes in the project. It is designed for stable projects and cannot handle project dynamics and uncertainties effectively. This results in inaccurate schedules and overall project performance. It is important to consider these limitations and potential drawbacks when utilizing the PERT method for project scheduling.

A Bayesian Network is a probabilistic model that can be used to depict the relationships among relevant variables in a system. This model is utilized to calculate the probability of an event based on the combination of several influencing variables[4]. In the context of project scheduling, Bayesian Networks can be employed to predict the duration of an activity based on various influencing factors such as resources, risks, and others. This Bayesian Network model enables users to consider uncertainty and risks occurring in the project, both quantitatively and qualitatively.

In reality, changes in project conditions, such as fluctuating resource availability such as materials, labor, and equipment availability, significantly impact project completion time. To avoid these issues, a more realistic probabilistic scheduling model is needed that aligns with the dynamic nature of actual project conditions. This study aims to propose a Hybrid Bayesian Network-PERT-based probabilistic scheduling model. This model combines the probabilistic scheduling method PERT with Bayesian Network. The PERT method is chosen because of its suitability for project activities with changing durations, and the Bayesian Network method is used to accommodate real-time changes in resource conditions for each project activity.

2 | PREVIOUS RESEARCHES

Several studies related to probabilistic scheduling have been conducted using one or a combination of several methods. Qiao[5] proposed a computational method that can calculate the probability of project completion based on the project type and its risk, forecasting using Bayesian Networks. Rezakhani[6] discussed the requirements of dynamic scheduling and monitoring tools during project execution using the fuzzy-Bayesian Network method. This method can assess the combined effects of multiple risk factors on activity duration and can control and predict productivity under uncertainty. However, from the analysis of project completion time, the steps for completion with this fuzzy method are complicated and difficult to apply in actual project planning[7].

Agyei[8] researched the trade-off between cost and the estimated minimum time required to complete a project using the PERT method. Nguyen et al.[9] utilized Bayesian Networks to model uncertainty and incorporated it into the CPM method, one of the

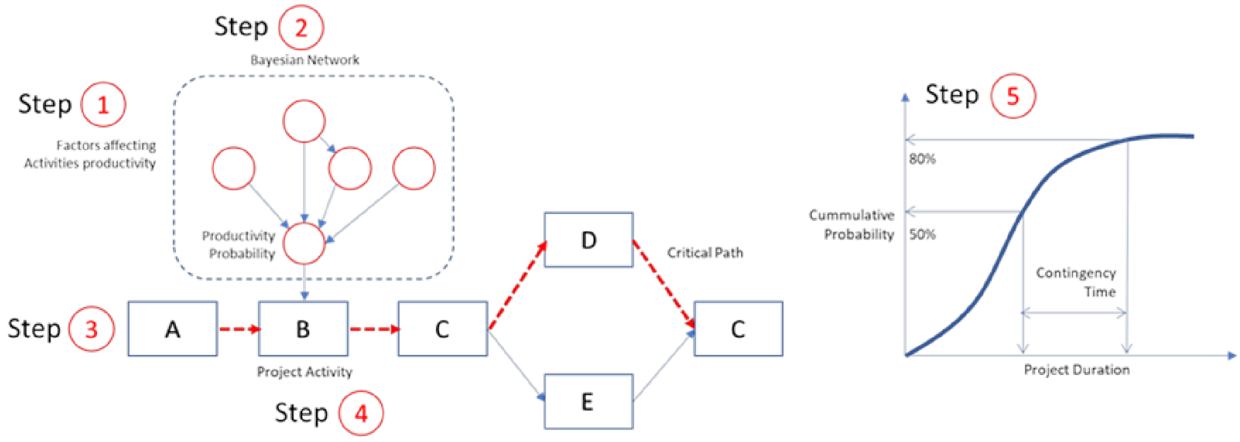

FIGURE 1 The stages of Hybrid Bayesian Network-PERT model construction.

most popular ways to monitor project scheduling. This paper also investigated common risk factors in project scheduling and proposed a model of 19 common risk factors. However, the CPM method can only be applied to project activities with constant and unchangeable durations. In reality, every project will encounter issues that will affect and change the duration of project activities.

Although many studies have been conducted in the field of Bayesian Networks and PERT, the integration of these two models has yet to be specifically explored. Both models have the potential to complement each other in the context of complex decision-making and efficient project planning. Combining Bayesian Networks with PERT can provide additional benefits by depicting the causal relationships between project activities and evaluating the impact of uncertainty on project scheduling. Therefore, the Bayesian Network-PERT model proposal could be an interesting research direction, offering a theoretical foundation and more comprehensive methods for project scheduling management.

3 | MATERIAL AND METHOD

3.1 | Material

Fig. 1 shows the steps for constructing the proposed model, Hybrid Bayesian Network-PERT. By following this procedure, a Bayesian-PERT model can be created more systematically and obtain useful information for project analysis.

Step 1 - Identify the Factors Affecting the Duration of Project Activities

The identification of factors influencing project duration was conducted to form a Bayesian Network model. The factors were grouped based on the influence of resources (labor, materials, and equipment) that affect project duration in real time. Based on an in-depth literature review, questionnaire distribution, and interviews with construction experts, 11 factors influencing the duration of bridge project activities were obtained and categorized as presented in Table 1 .

Step 2 - Bayesian Network Model

At this stage, a BN diagram is created to calculate the probability of labor productivity, equipment productivity, and material availability in each risky activity (See Fig. 2). The interdependency relationships between activities, states, and the transition probability matrix are obtained through a literature review and discussions with experienced experts in bridge construction projects.

Step 3 – Integration of Bayesian Network with PERT

The Bayesian network model that has been created is then integrated with the project schedule. Project activities are identified in terms of the risks that may affect the project duration. Fig. 3 shows how the Bayesian network is integrated with risky

TABLE 1 The identified factors that affect the duration of the project.

Category	Code	Factors	Reference
Work Productivity (W)	W1	Labor Supervision	Refaie et al.[10]
	W2	Worker Experience	Jalal and Shoar[11], Alaghbari et al.[12]
	W3	Good Communication	Jarkas et al.[13]
	W4	Management Leadership	Alaghbari et al.[12]
Equipment Productivity (E)	E1	Availability of Equipment	Chigara and Moyo[14]
	E2	Equipment Condition	Chigara and Moyo[14]
	E3	Operator skill	Jalal and Shoar[11]
Material Availability (M)	M1	Availability of Material Supplier	Thomas and Sudhakumar[15]
	M2	Late material delivery	Thomas and Sudhakumar[15]
	M3	Inflation	Adam et al.[16]

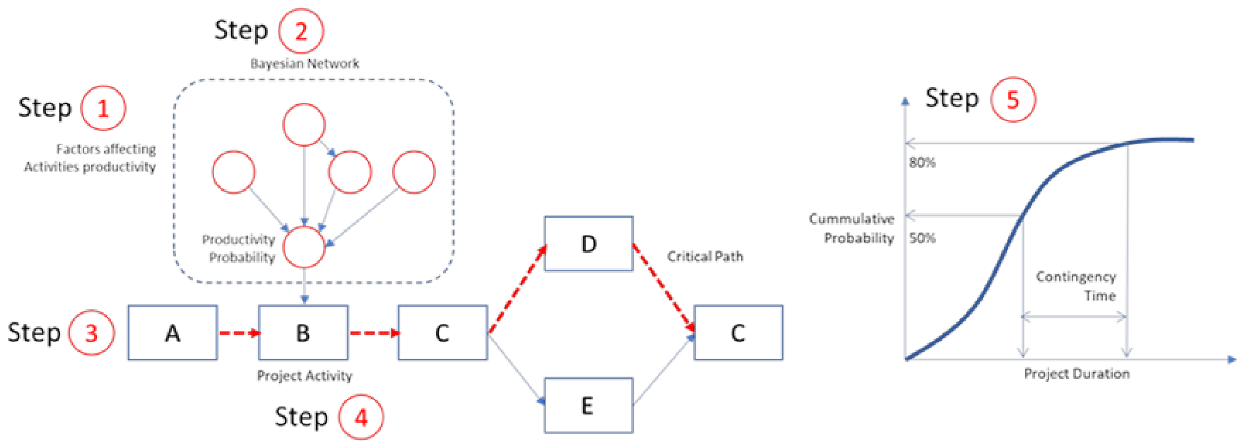

FIGURE 2 The bayesian network model for calculating the productivity of manpower, equipment, and availability of construction materials.

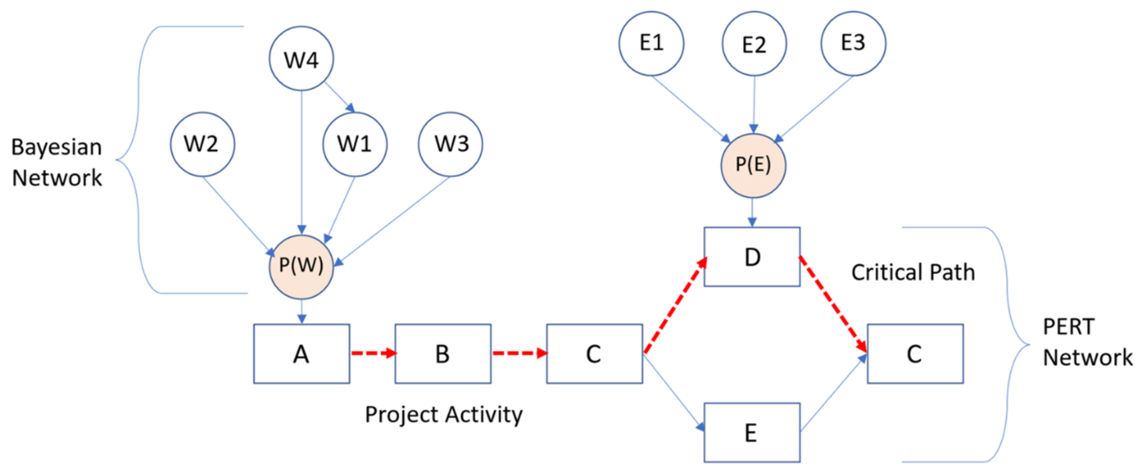

FIGURE 3 Bayesian network model in probability value of the risk.

project activities that may experience delays. If an activity is impacted by two resource risks, such as equipment and material availability, the Bayesian network model can be combined to obtain the probability value of the risk.

Step 4 – Calculation of Duration in Hybrid Bayesian-PERT

TABLE 2 The sequence and duration of project activities.

No	Activity	Description	Predecessor	Duration (days)
1	A	Preparation Work	-	10
2	B	Installation of Soil and Geosynthetics	A	21
3	C	Lower Structure (foundation)	B	63
4	D	Steel Upper Structure	C	40
5	E	Drainage Work	C	12
6	F	Miscellaneous Work	D, E	16

The calculation of optimistic (a), most likely (m), and pessimistic (b) duration estimates in the Hybrid Bayesian Network-PERT model is obtained by substituting the Bayesian probability values into the original duration (OD) of project activities, as shown in the following Eq. 1.

$$a = OD - [P(HighProductivity) \times OD] \tag{1}$$

Where:
$m = OD$
$b = OD + [P(HighProductivity) \times OD]$

Step 5 - Calculation of Project Completion Duration Probability

The calculation of expected activity time completion (te), standard deviation (S), and Variance ($S2$) are performed using the following formulas:

$$te = \frac{a + 4m + b}{6} \tag{2}$$

$$S = \frac{1}{6}(b - a) \tag{3}$$

$$S^2 = \left[\frac{b - a}{6}\right]^2 \tag{4}$$

The calculation of the probability of project time completion is performed using the following formula :

$$Z = \frac{Td - TE}{S_{CP}} \tag{5}$$

Where:
Z = Probability value based on normal distribution table.
Td = Target duration.
TE = Expected project time completion.
S_{CP} = Standard deviation of Critical Path.

4 | RESULTS

For the implementation and validation of the proposed model, the Kali Putih Bridge Project, with a bridge span of 60 meters located on Srumbung-Jurangjero Road, Magelang Regency, Central Java, Indonesia, is chosen as a case study. Table 2 shows the sequence and duration of each activity in the case study project. After the network diagram is created, the project's critical path is determined using the forward pass and backward pass methods.

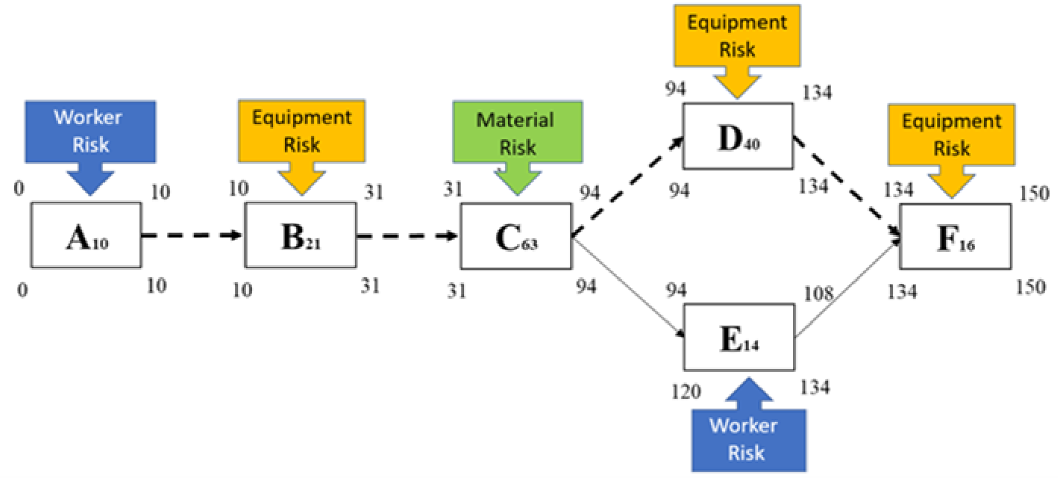

FIGURE 4 The identification of dominant risks in project activities.

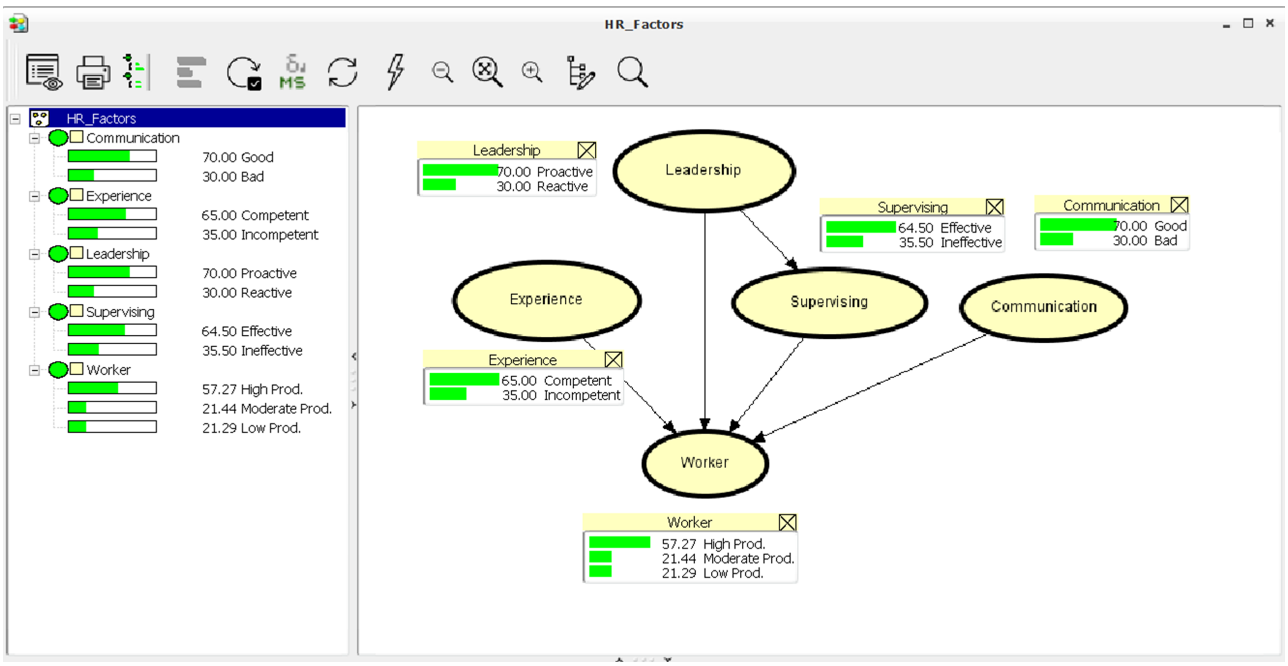

FIGURE 5 The simulation of the probability of labor productivity to activity under normal conditions (prior probability).

Based on the questionnaire results and interviews with experts, the dominant risks of each activity are presented in Fig. 4 .

From the interrelationship model of factors, as shown earlier, the probabilities of each factor are determined through questionnaires and interviews with project scheduling experts for the bridge project. The prior probability value for "competent" experienced and skilled construction workers is "0.65", while the probability of workers being "incompetent" is "0.35". In this project, the probability of "Good" communication between workers, staff, contractors, owners, and consultants is "0.70", while the probability of communication being "poor" is "0.30". By filling in the probabilities of these factors, the values of P(worker productivity = high) are 0.57, P(worker productivity = moderate) is "0.22", and P(worker productivity = low) is 0.21". The productivity of probability values for workers, equipment, and materials are presented in Table 3 . In this study, the calculation of probabilities is performed using the free Hugin lite 7.0 software. The process illustration of the BN calculation and its analysis results can be seen in Fig. 5 and Table 3 , respectively.

TABLE 3 The prior probability of workers, materials, and equipment.

Factor Category	State Probability			Factor
	High	Moderate	Low	Score
P (Worker Productivity)	0,5727	0,2144	0,2129	1,000
P (Materials Availability)	0,5848	0,2118	0,2034	1,000
P (Equipment Productivity)	0,5998	0,2134	0,1868	1,000

TABLE 4 The PERT parameter calculation.

ID	Job Definition	PD (days)	RF	ED (days)			*te* (days)	*S*	*Var*	Note
				a	m	b				
A	Preparation	10	Worker	4	10	12	9	1.31	1.71	Critical Path
B	Soil and Geosynthetics	21	Equipment	8	21	25	20	2.75	7.58	Critical Path
C	Structure	63	Material	26	63	76	59	8.28	68.49	Critical Path
D	Steel Upper Structure	40	Equipment	16	40	47	37	5.24	27.50	Critical Path
E	Drainage	14	Worker	6	14	17	13	1.83	3.36	Not Critical
F	Miscellaneous Work	16	Equipment	6	16	19	15	2.10	4.40	Critical Path

The conversion of durations a (optimistic), m (most likely), and b (pessimistic), after taking into account the probability of activity risks, is executed using Eq. 1.

- Planned duration of Activity A = 10 days.
- Dominant risk factor = Worker Productivity.
- Calculation results of Worker Productivity risk probabilities (see Table 3). High Productivity = 0.5727, Moderate Productivity = 0.2114, and Low Productivity: 0.2129.

$$
\begin{aligned}
a &= Original\ duration - [(P(Worker\ productivity = \text{“}high\text{”}) \times Original\ duration] \\
&= 10\ days - (0.5727x10\ days) \\
&= 4\ days \\
m &= 10\ days\ (Original\ duration) \\
b &= Original\ duration + [(P(Worker\ productivity = \text{“}low\text{”}) \times Original\ duration] \\
&= 10\ days + (0.2129 \times 10\ days) \\
&= 12\ days
\end{aligned}
$$

Based on Eq. 1, 2,3, and 4, the expected activity time (te), standard deviation (Sd), and variation (S2) for each project activity can be calculated and seen in Table 4 . It also shows plan duration (PD) in days, the most dominant risk factor (RF), and estimated durations (ED) in days for each job definition.

The PERT network diagram can be created based on the data generated in Table 4 . Fig. 6 shows the network diagram and critical path of the Bridge project. It can be observed in Fig. 6 that the proposed model estimates the project completion to be 140 days, with a project standard deviation of 10.47 days (standard deviation on the critical path). Therefore the range of Project Completion Time is 140 ± 10.47 days. It is also noticeable that each activity has a variation in duration (Eq. 4). This indicates that the risk aspect is already accounted for in the duration of each project activity.

5 | DISCUSSION

Comparison Analysis of Simulation Results between the Hybrid Bayesian Network - PERT Model and Actual Project Schedule The actual project time completion is inputted into the model to validate this proposed model. Based on the S-curve data of the Kali Putih Bridge Project, the actual project completion duration is 150 days. Using Eq. 5, the probability of project completion time is calculated, and a Cumulative Distribution Function (CDF) of the estimated project completion time is created.

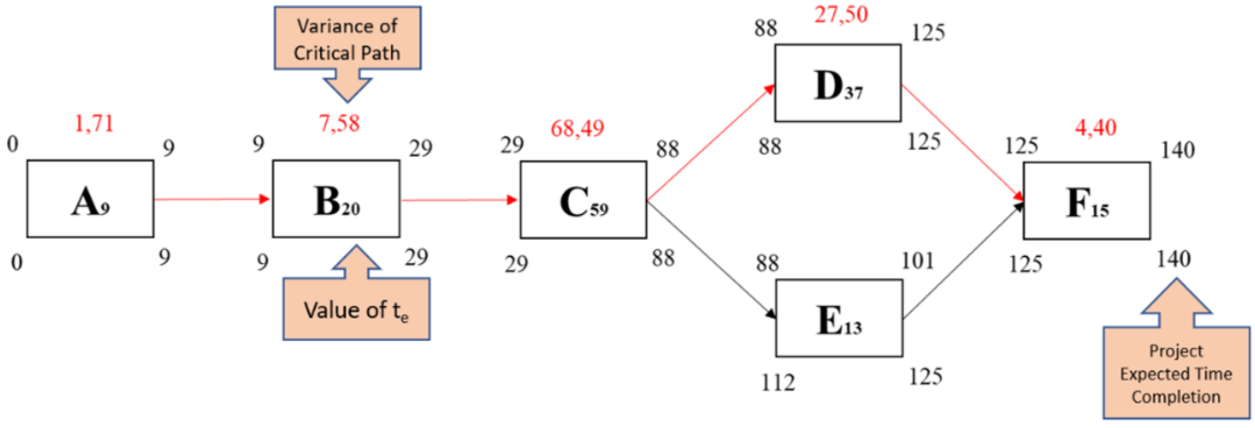

FIGURE 6 The estimated duration of project completion.

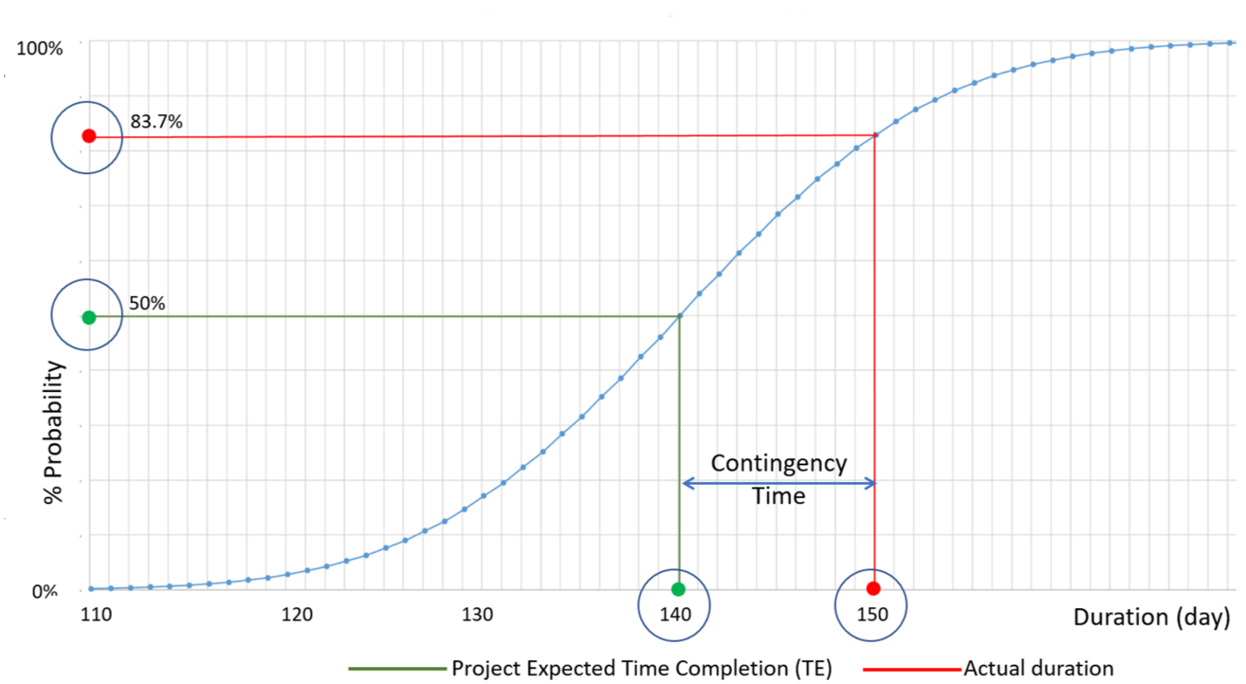

FIGURE 7 The CDF graph of the probability of Project Time Completion.

Fig. 7 shows that the probability of the actual project duration being completed in 150 days is 83.7%. The target completion duration (TE) with the proposed hybrid Bayesian-PERT model is 140 days, and the actual project completion duration is 150 days. The project completion deviation of 10.47 days indicates that the acceptable maximum contingency time is 150.47 days. This means that the actual project completion is still within the calculated contingency time limit by the model. The model's deviation prediction error is ten days, resulting in an error calculation of 10 days/150 days = 6.6%. This implies that the model has an accuracy of 93.4% in predicting project completion time.

Based on the above results, the proposed model and has good predictive accuracy can be used. This model can be implemented in actual projects by incorporating risk aspects (both quantitative and qualitative) through the BN diagram. The findings strengthen the previous studies conducted by Qiao[5] and Rezakhani[6], who claimed that BN could accommodate any changes and how it affects the project schedule.

6 | CONCLUSION

The proposed Hybrid Bayesian-PERT model can address the limitations of the PERT method, where the calculation of a, m, and b durations no longer relies on historical data but can be updated in real-time based on on-site conditions. The model allows for the incorporation of resource risk aspects such as changes in worker productivity, equipment availability, and material availability in real-time using the Bayesian Network (BN). The BN can accommodate both qualitative and quantitative risk factors, enabling the model to depict on-site conditions realistically. From the validation test results, the model demonstrates a prediction accuracy of 93.4% in project completion time. The Hybrid Bayesian-PERT model can assist practitioners, professionals, and relevant stakeholders in formulating strategies related to actual on-site risks, thereby improving resource productivity for on-time project completion as planned.

CREDIT

Tri Joko Wahyu Adi: Conceptualization, Methodology, Validation, Resources, Data Curation, Writing - Original Draft, and Visualization. **Farida Rachmawati:** Methodology, Validation, Writing - Review & Editing, and Supervision. **Safira Yulia Rizky:** Software, Investigation, and Formal analysis.

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