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Project Completion Probability Analysis Based on Bayesian Network

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Abstract: *In the case of not considering the risk, the calculation of the completion probability of the project by Bayesian network will exaggerate the calculation result. Based on this problem, the calculation method of the completion probability of a project affected by risks is proposed. This paper first analyzes the differences between Bayesian network considering risks or not, and establishes a new Bayesian network model based on the advantages of Bayesian network calculating probability and the risk situation encountered in construction. Then, it introduces the calculation method of completion probability considering risk, which mainly includes three types: one is only affected by one of the predecessor activities and risks: the other is affected by both, but the predecessor activities and the current work are not affected by the same risks; the third is the two work are affected by the same risk factors. Calculate the completion probability of the work until the last work based on the above method. Finally, Combined the model with an example to verify its effectiveness. By comparing the completion probability considering risks with that not considering risks, we can see that due to the uncertainty of the environment, the model considering risks has a wider application in the project. It can calculate the completion probability according to the real-time situation and help constructors take measures to ensure its completion in time, which also provides an effective decision basis for project constructors and project builders.*

Keywords: *Bayesian network, probability of completion, risk, predecessor activities*

1. Introduction

With the steady development of China's economy, the construction project is also striding forward. Our builders have gradually moved abroad, our constructions are more and more approved by the world. In 2017, China sent 222, 135 labor workers to the world for the construction projects, and the turnover reached 16.85 billion dollars. In 2018, the turnover of world contracted projects reached 16.94 billion dollars. All above data shows the influence of our construction project in foreign countries. For construction project all over the world, there are three major goals: quality, safety and project period. The quality of construction relies on the materials and construction technology to ensure. Project management is an important means to ensure construction safety. But the project period is affected by a series of uncertain factors, so it is the most uncontrollable aspect. If you have any work delay which affects the period, we need to accelerate the back closely activities or adjust the construction organization to make the project completed on schedule. For the construction units, profit is their fundamental goal, and the project period is also an important part to improve their profit. For the owner unit, the project completed on time will help its utility play better, if the Bird's Nest Stadium has not completed before the Olympic Games, China can’t hold the Olympic Games successfully. If that happened, it weren’t only economic loss, but also hurt China's image and ability in front of the rest of the world. So a project completed on time is vital for all units.

To grasp the probability of completion of a project is an important measure to ensure that the project is completed on time. If there is any discrepancy between the project and the planned time limit, it is necessary to take timely measures to remedy it, so as to ensure that the project is completed on time.Xu Xiaochun [1] proposed to use PERT to estimate project risks in advance, so as to avoid blind implementation of the plan.Jin Dezhi et al. [2] pointed out that in the case of clear logical relationship and uncertain working time, PERT method could calculate the probability of project completion within the planned time limit. Wang Zhuofu et al. [3] obtained the calculation method of completion probability of such projects through the study of several key lines with and without correlation. Chen Yuehua et al. [4] improved PERT by using the key chain method, solved the problems of resource constraint and human influence in the project, and obtained a more effective method for project group risk management.Bian Liming et al. [5] obtained more accurate completion probability of lap network through Monte Carlo method.

PERT method is used to calculate the static risk and completion probability, but in the process of construction, there are different risk factors influencing the progress of the work, and then affect the completion probability. So we need to adjust the process to obtain the value at risk or completion probability. Jia Huanjun [6] through the whole density of project period , cost and quality calculated the probability of events happened or where the risk value event will fall; Chen Yongqiang et al. [7] obtained the factors affecting the selection of project transaction through the Bayesian network and then made sensitivity analysis to obtain the influence of each factor on project performance, which provided a basis for the choice of transaction mode and deepened the understanding and cognition of engineering parties on the nature of transaction mode.Xiang Yong et al. [8] analyzed the impact of risks on project period from the aspects of project participants, project materials and force majeure by using Bayesian network, and introduced the principle of non-superposition to conclude that the effect of multiple factors is not equal to the sum of the effects of a single factor, and comprehensively proved the impact factors of project duration risk.He Qinghua et al. [9] used bayesian network model to deduce and predict whether the project schedule is behind by identifying key sensitive risk factors of complex projects, and put forward relevant risk management suggestions. Huang Jianwen et al. [10] calculated completion probability through PERT method and Bayesian network method. They concluded that Bayesian network method can solve the limitation of large completion probability calculation in case of difference between hypothesis and reality, thus improving the accuracy of completion probability calculation through the comparison of results.

Moreover, Bayesian networks can be applied in many ways.Min Li et al. [11] and Golam Kabir et al. [12] analyzed mine fire sources and earthquake risks through Bayesian network model, and identified the causes of gas explosions better, which provided a basis for coal mine analysts and decision makers, could predict and diagnose future earthquakes.LIU Yang et al. [13] applied Bayesian network to the risk analysis of geotechnical engineering. This method can better solve the overfitting problem that often occurs in the risk assessment of geotechnical engineering, and can also effectively evaluate various geotechnical engineering risks without some factors. Satyendra Kumar Sharma et al.[14]put forward that Bayesian model can effectively capture the interaction between various risk factors. It can help the project manager predict the failure risk probability of R&D project. Nini Xia et al.[15] put forward a Bayesian risk analysis framework across the project period. It helped further understand the dynamics and the large infrastructure lifecycle stages associated risk. Eunchang Lee [16] applied Bayesian network of large engineering project risk management to South Korea shipbuilding industry. It help better understand the risks of Korean shipbuilding industry. Van Truong Luu et al.[17] applied Bayesian network to quantify the probability of construction delay in developing countries and verified its effectiveness. All above scholars proved the applicability of the Bayesian network in construction project .They also do many analysis and calculation in project risk and completion probability. But it lacks the study of project completion probability under specific risks. In this paper, on the premise of considering the project risk based on the Bayesian network calculating the completion probability. The result can help provide more accurate information to help policymakers and builders choose the more appropriate management approach.

2. Risk Factor Analysis

In this paper, it calculates the completion probability by considering the internal and external risks . The internal and external here is relative to the project participants. The internal risk is formed by the constructor personnel experience of design unit, management, qualifications, technology and construction organization, the most important thing is that whether the three units have communication and cooperation. External factors come from the government and the natural environment. Recently on the premise of our country attaching great importance to green development, the environment is one important factor that help the government whether the project can be implemented. For example, when the project is located in where its PM2.5 index exceeds standard, the government will require the construction to cease to protect the urban environment. In addition, there are national large conference held at the location of the project, its progress will be affected. The natural environment risk consists of weather and natural disasters. Except the predictable weather factors, the other unknown factors are the major cause affecting the project period to consider. For example average amount of rainy days each year and the amount of precipitation need to be considered during prepare the construction organization design. During the project , if encountered the natural disasters such as earthquake and tsunami. It doesn’t not affect the interest of the construction unit, but the project period will be affected.

If the project is similar to the Bird's Nest project, even if encounter the unpredictable risks it must finish on time. So this paper will consider all the risk factors influencing the project period, and then calculate the completion probability, rather than just consider about the risks relevant to the construction builders

3. Completion Probability Model

3.1 Basic Principle

Bayesian networkis an extension of Bayesian method, was proposed by Pearl in 1988 and has become a research hotspot in recent years.

Bayesian network is a directed acyclic graph, composed of nodes and directed arcs. Nodes represent random variables, directed arcs represent the causal relationship between the two nodes(from parent to child node), its causation is usually expressed by conditional probability between parent and child nodes. Give the piror probability directly which boundary nodes have no parent node and then calculate the posterior probability of the other nodes.

Let's call the variable set $A=\{A_1, A_2, \ldots\ldots A_n\}$, The values of each variable are $A_i=\{a_{i1}, a_{i2}\ldots a_{ik}\}$, $i=1,2\ldots n$ Then the probability of a child node is:

$$\mathrm{P}\left(A_k=a_{k1}\right)=\sum_{\pi} P\left(A_k=a_{k1} | \pi\left(A_k\right)\right) \tag{1}$$

Where: $\pi\left(A_k\right)$ represent the joint distribution of the parent nodes of A_k. Assume the Bayesian network as shown in Fig. 1 below.

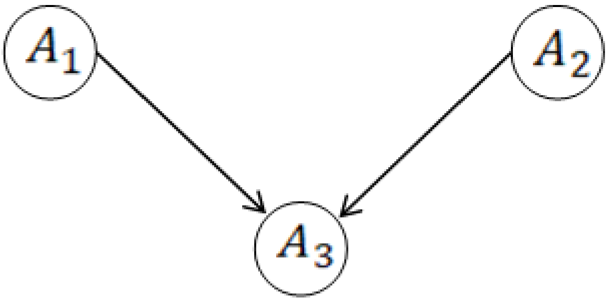

Figure 1: Bayesian network

A_1, A_2 are two parent nodes of A_3, And they're independent of each other, It respectively has two values a_{11}, a_{12} and a_{21}, a_{22}, A_3 is the child node, It has values of a_{31}, a_{32}, Find the probability of different values of A_3, then:

$$\begin{aligned} P\left(A_3=a_{31}\right)= & P\left(A_1=a_{11}\right)\times P\left(A_2=a_{21}\right)\times P\left(A_3=a_{31} | A_1=a_{11}, A_2=a_{21}\right)+ \\ & P\left(A_1=a_{11}\right)\times P\left(A_2=a_{22}\right)\times P\left(A_3=a_{31} | A_1=a_{11}, A_2=a_{22}\right)+ \\ & P\left(A_1=a_{12}\right)\times P\left(A_2=a_{21}\right)\times P\left(A_3=a_{31} | A_1=a_{12}, A_2=a_{21}\right)+ \\ & P\left(A_1=a_{12}\right)\times P\left(A_2=a_{22}\right)\times P\left(A_3=a_{31} | A_1=a_{12}, A_2=a_{22}\right) \end{aligned} \tag{2}$$

$$\begin{aligned} P\left(A_3=a_{32}\right)= & P\left(A_1=a_{11}\right)\times P\left(A_2=a_{21}\right)\times P\left(A_3=a_{32} | A_1=a_{11}, A_2=a_{21}\right)+ \\ & P\left(A_1=a_{11}\right)\times P\left(A_2=a_{22}\right)\times P\left(A_3=a_{32} | A_1=a_{11}, A_2=a_{22}\right)+ \\ & P\left(A_1=a_{12}\right)\times P\left(A_2=a_{21}\right)\times P\left(A_3=a_{32} | A_1=a_{12}, A_2=a_{21}\right)+ \\ & P\left(A_1=a_{12}\right)\times P\left(A_2=a_{22}\right)\times P\left(A_3=a_{32} | A_1=a_{12}, A_2=a_{22}\right) \end{aligned} \tag{3}$$

It can be seen from the above formula that the different probabilities of A_3 is affected by its parent

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nodes probability of different values and the relationship between parent and child nodes. between parent and child nodes.

3.2 Model Building

Bayesian network completion probability model considering risk increases risk factors for different activities. First you need to consider the probability of risk occurrence named prior probability of Bayesian network, and then calculate activities probability affected by the risk and predecessor activities status, finally calculate the whole project completion probability.

(1) Determine the risk factors affecting each activity as the parent node of the work; $R = \left(R_1, R_2 \ldots R_m\right)$, All values are 0 or 1. "0" means that the risk event does not occur, and "1" means that the risk event occurs.

(2) Determine each activity node of the project $A = \left(A_1, A_2 \ldots A_n\right)$, All values are Y or N, "Y" means the work is completed on time, and "N" means the work is not completed on time;

(3) Establish a Bayesian network based on the risk factors and the logical relationship between each work;

(4) According to the construction experience and expert analysis results, calculate the probability of each risk event occurrence and the completion probability of each work under the influence of risk factors;

(5) Calcualte the completion probability of each work node.

3.3 Completion Probability Calculation

The probability of completion in Bayesian network is the probability that the end node has a value of "Y". Let A be a work node in Bayesian network, $B_i\left(i=1,2\ldots n\right)$ is the c predecessor activity node of A, $R_{ai}\left(i=1,2,\ldots k\right)$ is the risk factors affecting A, $R_{ij}\left(i=1,2\ldots n, j=1,2\ldots m\right)$ is the risk factors affecting B_i, The completion probability of node A can be calculated by the formula

(1) If node A has no predecessor activities (risk), it is only affected by risk factors R_{ai} (predecessor activities B_i) Then the completion probability of A can be expressed as:

$$\mathrm{P}\left(A=Y\right)=\sum_{\pi}\left(\prod_{i=1}^{k}P\left(R_{ai}\right)\times P\left(A=Y|\pi\left(R_a\right)\right)\right) \tag{4}$$

$$P\left(A=Y\right)=\sum_{\pi}\left(\prod_{i=1}^{n}P\left(B_i\right)\prod_{i=1}^{k}P\left(R_{ai}\right)\times P\left(A=Y|\pi\left(R_a,B\right)\right)\right) \tag{5}$$

Where: $\pi\left(R_a\right)$ represents a distribution of k risks R_{ai} ($\pi\left(B\right)$ represents a distribution of k predecessor activities B_i)

Assume that node A is only affected by two risk factors (two predecessor activities), its completion probability can be written as:

$$\begin{aligned}P(A=Y)=&P(R_1=1)\times P(R_2=1)\times P(A=Y\left|R_1=1,R_2=1\right)\\&+P(R_1=1)\times P(R_2=0)\times P(A=Y\left|R_1=1,R_2=0\right)\\&+P(R_1=0)\times P(R_2=1)\times P(A=Y\left|R_1=0,R_2=1\right)\\&+P(R_1=0)\times P(R_2=0)\times P(A=Y\left|R_1=0,R_2=0\right)\end{aligned} \tag{6}$$

(2) Considering that node A has predecessor activities B_i and are affected by risk factor R_{ai}, and that A and its predecessor activities B_i are not affected by the same risk factor, the completion

probability of A can be expressed as:

$$P\left(A=Y\right)=\sum_{\pi}\left(\prod_{i=1}^{n}P\left(B_i\right)\prod_{i=1}^{k}P\left(R_{ai}\right)\times P\left(A=Y|\pi\left(R_a,B\right)\right)\right) \tag{7}$$

Where: $\pi\left(R_a,B\right)$ represents a distribution of N predecessor activities and k risks;

Assume that *A* has two predecessor activities, they are B_1 and B_2, the three have no same risk factors. *A* is only affected by risk R_{a1}, the completion probability of node A can be written as:

$$\begin{aligned}P\left(A=Y\right)=&P\left(R_{a1}=0\right)\times P\left(A=Y|R_{a1}=0,B_1=Y,B_2=Y\right)\times P\left(B_1=Y\right)\times P\left(B_2=Y\right)\\&+P\left(R_{a1}=0\right)\times P\left(B_1=Y\right)\times P\left(B_2=N\right)\times P\left(A=Y|R_{a1}=0,B_1=Y,B_2=N\right)\\&+P\left(R_{a1}=0\right)\times P\left(A=Y|R_{a1}=0,B_1=N,B_2=Y\right)\times P\left(B_1=N\right)\times P\left(B_2=Y\right)\\&+P\left(R_{a1}=0\right)\times P\left(B_1=N\right)\times P\left(B_2=N\right)\times P\left(A=Y|R_{a1}=0,B_1=N,B_2=N\right)\\&+P\left(R_{a1}=1\right)\times P\left(A=Y|R_{a1}=1,B_1=Y,B_2=Y\right)\times P\left(B_1=Y\right)\times P\left(B_2=Y\right)\\&+P\left(R_{a1}=1\right)\times P\left(B_1=Y\right)\times P\left(B_2=N\right)\times P\left(A=Y|R_{a1}=1,B_1=Y,B_2=N\right)\end{aligned} \tag{8}$$

(3) Consider that there are predecessor activities B_{i} and C_{j} before node A, where C_{j} is predecessor activity without the same risk factors as *A*, B_{i} is predecessor activity with the same risk factors $R_{ab\mathrm{ip}}$ as A, and $R_{a\mathrm{q}}$ is a risk factor affecting A but different from B_{i} and C_{j}, the completion probability of *A* can be written as:

$$P\left(A=Y\right)=\sum_{\pi}\left\{\prod_{\mathrm{q=1}}^{\mathrm{k}}P\left(R_{a\mathrm{q}}\right)\times\prod_{\mathrm{i=1}}^{n-\mathrm{m}}\left[\prod_{\mathrm{p=1}}^{\mathrm{l}}P\left(R_{ab\mathrm{ip}}\right)\times P\left(B_i|\pi_{\mathrm{b}}(R_{ab\mathrm{ip}})\right)\right]\times\prod_{\mathrm{j=1}}^{\mathrm{m}}P\left(C_{\mathrm{j}}\right)\times P\left(A=Y|\pi\left(C_{\mathrm{j}},R_{a\mathrm{q}},B_i,R_{ab\mathrm{ip}}\right)\right)\right\} \tag{9}$$

Where: $\pi_{\mathrm{b}}(R_{ab\mathrm{ip}})$ represents A distribution of common risk factors between A and B_{i}; $\pi\left(C_{\mathrm{j}},R_{a\mathrm{q}},B_i,R_{ab\mathrm{ip}}\right)$ represents a distribution of n predecessor activities and $(\mathrm{k}+\sum_{\mathrm{i=1}}^{\mathrm{n-m}}\mathrm{l})$ risk;

Assume that node A has predecessor activities C and B, risk factors R_1 and R_2, where R_1 is the risk that only affects A, R_2 is the risk that affects A and B, then the completion probability of A is:

$$\begin{aligned}P\left(A=Y\right)=&P\left(C=Y\right)\times P\left(R_1=0\right)\times P\left(R_2=0\right)\times P\left(B=Y|R_2=0\right)\times P\left(A=Y|C=Y,R_1=0,R_2=0,\mathrm{B=Y}\right)\\&+P\left(C=Y\right)\times P\left(R_1=0\right)\times P\left(R_2=0\right)\times P\left(B=N|R_2=0\right)\times P\left(A=Y|C=Y,R_1=0,R_2=0,\mathrm{B=N}\right)\\&+P\left(C=Y\right)\times P\left(R_1=0\right)\times P\left(R_2=0\right)\times P\left(B=N|R_2=0\right)\times P\left(A=Y|C=Y,R_1=0,R_2=0,\mathrm{B=N}\right)\\&+P\left(C=Y\right)\times P\left(R_1=0\right)\times P\left(R_2=1\right)\times P\left(B=N|R_2=1\right)\times P\left(A=Y|C=Y,R_1=0,R_2=1,\mathrm{B=N}\right)\\&+P\left(C=Y\right)\times P\left(R_1=1\right)\times P\left(R_2=0\right)\times P\left(B=Y|R_2=0\right)\times P\left(A=Y|C=Y,R_1=1,R_2=0,\mathrm{B=Y}\right)\\&+P\left(C=Y\right)\times P\left(R_1=1\right)\times P\left(R_2=0\right)\times P\left(B=N|R_2=0\right)\times P\left(A=Y|C=Y,R_1=1,R_2=0,\mathrm{B=N}\right)\\&+P\left(C=Y\right)\times P\left(R_1=1\right)\times P\left(R_2=1\right)\times P\left(B=Y|R_2=1\right)\times P\left(A=Y|C=Y,R_1=1,R_2=1,\mathrm{B=Y}\right)\\&+P\left(C=Y\right)\times P\left(R_1=1\right)\times P\left(R_2=1\right)\times P\left(B=N|R_2=1\right)\times P\left(A=Y|C=Y,R_1=1,R_2=1,\mathrm{B=N}\right)\\&+P\left(C=N\right)\times P\left(R_1=1\right)\times P\left(R_2=0\right)\times P\left(B=Y|R_2=0\right)\times P\left(A=Y|C=N,R_1=1,R_2=0,\mathrm{B=Y}\right)\\&+P\left(C=N\right)\times P\left(R_1=1\right)\times P\left(R_2=0\right)\times P\left(B=N|R_2=0\right)\times P\left(A=Y|C=N,R_1=1,R_2=0,\mathrm{B=N}\right)\\&+P\left(C=N\right)\times P\left(R_1=1\right)\times P\left(R_2=1\right)\times P\left(B=Y|R_2=1\right)\times P\left(A=Y|C=N,R_1=1,R_2=1,\mathrm{B=Y}\right)\\&+P\left(C=N\right)\times\times P\left(R_1=1\right)\times P\left(R_2=1\right)P\left(B=N|R_2=1\right)\times P\left(A=Y|C=N,R_1=1,R_2=1,\mathrm{B=N}\right)\\&+P\left(C=N\right)\times P\left(R_1=0\right)\times P\left(R_2=0\right)\times P\left(B=Y|R_2=0\right)\times P\left(A=Y|C=N,R_1=0,R_2=0,\mathrm{B=Y}\right)\\&+P\left(C=N\right)\times P\left(R_1=0\right)\times P\left(R_2=0\right)\times P\left(B=N|R_2=0\right)\times P\left(A=Y|C=N,R_1=0,R_2=0,\mathrm{B=N}\right)\\&+P\left(C=N\right)\times P\left(R_1=0\right)\times P\left(R_2=1\right)\times P\left(B=Y|R_2=1\right)\times P\left(A=Y|C=N,R_1=0,R_2=1,\mathrm{B=Y}\right)\\&+P\left(C=N\right)\times P\left(R_1=0\right)\times P\left(R_2=1\right)\times P\left(B=N|R_2=1\right)\times P\left(A=Y|C=N,R_1=0,R_2=1,\mathrm{B=N}\right)\end{aligned} \tag{10}$$

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4. Case Analysis

The construction project network diagram with risk factors is shown in Figure 2.

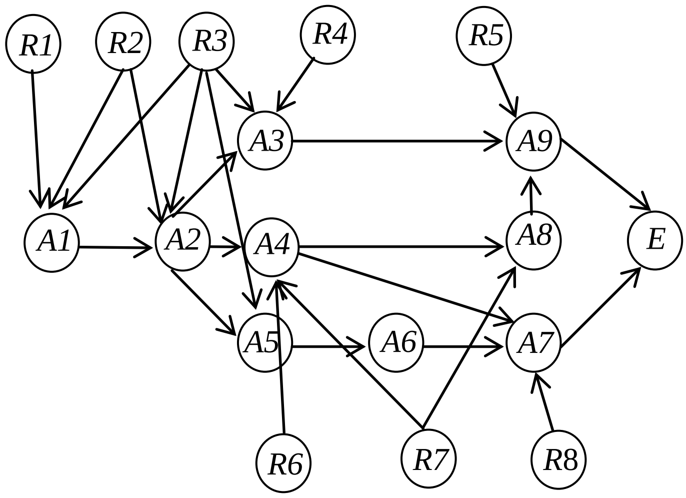
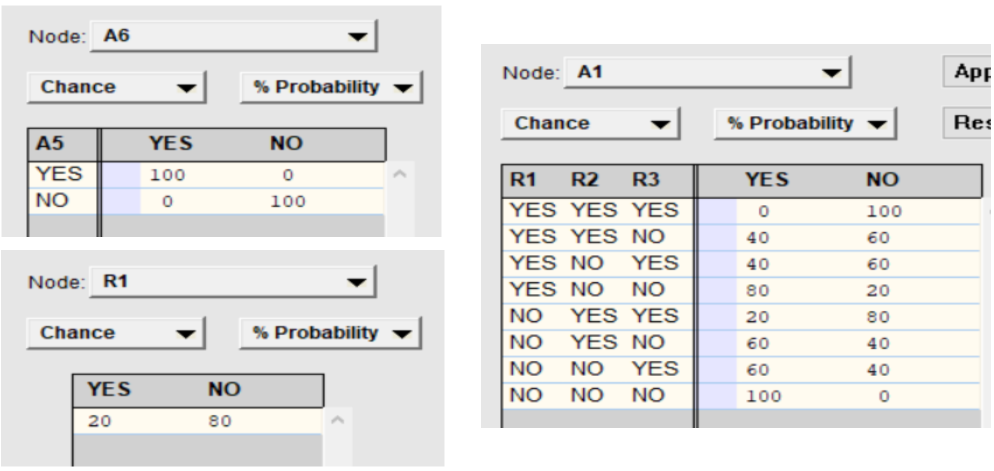


Figure 2: Engineering network

In the network diagram, the boundary node is risk nodes, the set is $J=\{R_1,R_2,R_3,R_4,R_5,R_6,R_7,R_8\}$, the set of child nodes only affected by the risk is $J_1=\{A_1\}$, the set of child nodes only affected by predecessor activities is $J_2=\{A_6,E\}$, the set of child nodes affected by both risks and predecessor activities but without the same risk factors as the predecessor activities is $J_3=\{A_4,A_7,A_9\}$, the set of child nodes affected by both risks and predecessor activities with the same risk factors as the predecessor activities is $J_4=\{A_2,A_3,A_5,A_8\}$. Then the completion probability of all nodes in the Bayesian network is calculated according to the calculation formula above.

The data in this paper comes from a construction project. Input the nodes and their logical relations of the project into NETICA to establish Bayesian network, and then input the probability from experts estimated probability of risk occurrence, completion probability of nodes under risk, and conditional probability between activities, as shown in Figure. 3 below.



Node: A6 | Chance | % Probability

A5	YES	NO
YES	100	0
NO	0	100

Node: R1 | Chance | % Probability

YES	NO
20	80

Node: A1 | Chance | % Probability | App | Res

R1	R2	R3	YES	NO
YES	YES	YES	0	100
YES	YES	NO	40	60
YES	NO	YES	40	60
YES	NO	NO	80	20
NO	YES	YES	20	80
NO	YES	NO	60	40
NO	NO	YES	60	40
NO	NO	NO	100	0

Figure 3: Bayesian network conditional probability

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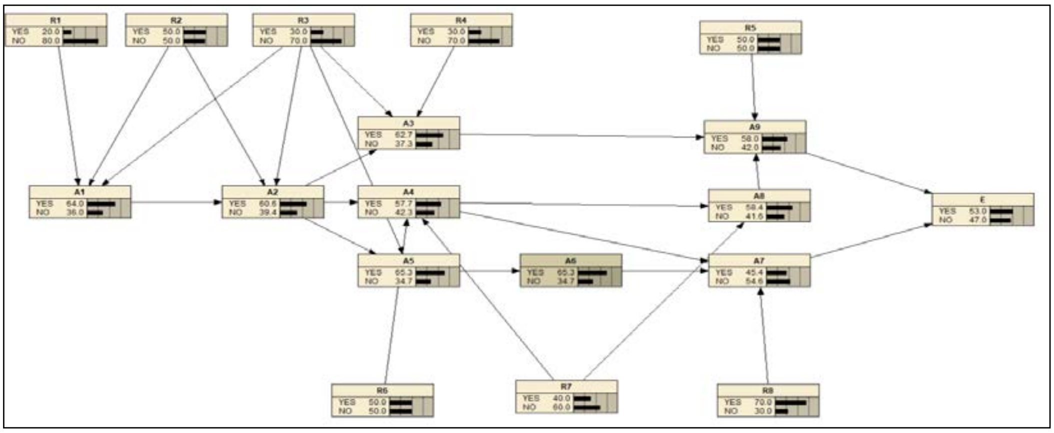

Figure 4: Probability of completion under risk

After calculation, the project completion probability is 53.0%, as shown in Figure.4, and the completion probability without considering risks is 73.5%, as shown in Figure.5

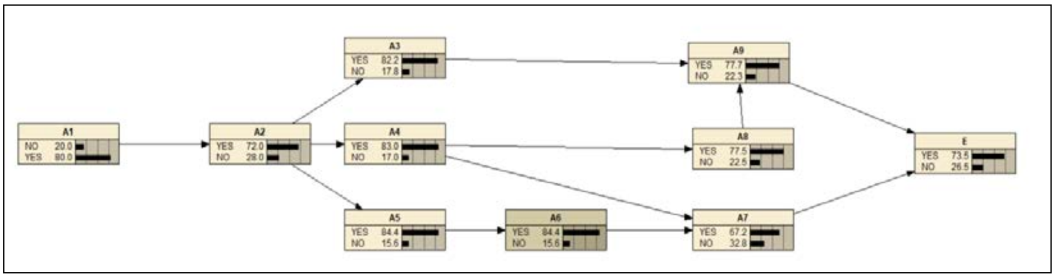

Figure 5: Probability of completion

The completion probability in Figure 5 is calculated only based on predecessor activities completion probability, but a predecessor activity completion probability is calculated by the conditional probability integrated with historical risks. The probability calculation method is similar to the above, but simplifies quantitative discussion of risk impact just based on qualitative risk estimate from the experts without considering the completion probability after risks occur.

As can be seen from the figure above, the completion probability calculated under taking risks into account is lower than that without taking risks into account. Therefore, the completion probability of the whole project is reduced by 20.5%. The main reasons are as follows:

1, Compared with considering the risk occurs or not, different projects have different risks, experts just pre-judge the conditional probability between predecessor activities and successor activity and completion probability of work according to the experience without considering the risk occurrence in detail. The risks they consider are the average probability of risk occurring. The estimated value of completion probability will be larger.

2, In case of considering the probability of the risk occurring, not only to integrate all risks to calculate the completion probability, also consider the risk of each work and the completion probability of each work under the risks occurs or not. Based on those the result will be lower than that calculated only under predecessor activities. Although the dynamic impact of risk on completion probability is considered in this paper, the level of risk and the level of impact on completion probability are not specifically classified. And the level of risk and its impact on the project are of great significance to the management of the construction unit and the owner.

5. Conclusion

(1) In this paper, risk factors are added to calculate completion probability based on Bayesian network. The result is lower than the completion probability without considering the risk before. This paper presents the calculation method cancalculate completion probability according to the type of project and the risk forecasting. And then input the risk data in the network to recalculate the result. It

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can help the correspondent unit timely adjust their subsequent construction plan to ensure the project period. Compared with the previous work completion probability before incorporating risk into the predecessor activities, this method is more intuitive to understand the influence of various risks to project completion, such as the weather reason, policy reason and other factors that influence the project period. There will be a pre-judgment for the completion probability of the construction unit in advance, according to the relevant departments notification of the risk occurrence probability. So that it can take measures in the construction process.Therefore, the method in this paper is not only helpful for the construction unit to control beforehand, but also can dynamically adjust the completion probability after the occurrence of the risks, which reflects the dynamic change of the completion probability of the whole project. It not only meets the construction unit to ensure the completion, but also meets requirement of the owner to understand the project schedule.

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