Analysing the Risk Propagation in the Project Portfolio Network using the *SIRF* Model

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Keywords: Portfolio Risk, *SIRF* (Susceptible-Infected-Recovered-Failed) Model, Risk Propagation, K-shell, Centrality of Eigenvectors, Link Entropy.

Abstract: Due to the existence of dependencies among the projects, the risk in one project will cause risks in other projects, which will lead to the risk propagation in the portfolio network. To measure the criticality of projects in the portfolio considering risk propagation, the paper builds the risk analysis model using the complex network and *SIRF* model. Firstly, we build the network of the project portfolio based on the analysis of the independency among projects, then we propose the integrated project criticality measurement (*IPCM*) algorithm based on the complex network theory. The *IPCM* algorithm integrates the K-shell, eigenvector centrality and the neighbour nodes in the complex network to analyse the project criticality. Furthermore, the link entropy is used to calculate the influence of the project in the network. On this basis, combined with the practice of R&D project management, the *SIRF* (susceptible-infected-recovered-failed) model is proposed to analyse the dynamic propagation process of the risk in the project portfolio network. Then the priority ranking of the project portfolio is realized under the dynamic risk propagation. Finally, a representative example is provided to illustrate the validity of proposed models.

1 INTRODUCTION

Project portfolio is a collection of projects, project sets, sub-project portfolios, and operations that are managed together to achieve strategic goals (Project Management Institute, 2018). Due to the existence of dependencies between projects, the occurrence of risks in a certain project will make other projects risky, which will lead to the "domino effect" in the portfolio, and ultimately lead to the failure of the entire project portfolio (Neumeier et al., 2018). Aiming at the shortcomings of the traditional project portfolio criticality analysis that ignore the dynamic spread of risk in the project portfolio, the paper uses *SIR* (susceptible-infected-recovered) model to analyse the project portfolio risk. The *SIR* is often used to describe the spread of diseases, viruses and rumours in social network (Wen et al., 2012). Similar to the spread of infectious diseases in the population, the propagation of risk in the portfolio also conforms to the dynamics of complex networks. Therefore, depending on the analysis of the portfolio, the paper extends the traditional *SIR* model to the *SIRF* (susceptible-infected-recovered-failed) to analyse the dynamic propagation process of the risk, and then measure the criticality of projects in the portfolio.

The paper measures the criticality of projects using the complex network theory. The node centrality is widely used to identify influential nodes in the network (Liu et al., 2015). Among them, the K-shell measures the importance based on the location attribute. The Kitsak et al. (2010) pointed out that the most influential node in the network is not the node with the largest degree value, but the node at the core position of the network obtained through K-shell decomposition. It means that the position of a node in the network determines its criticality, that is, the higher the Ks value of the node in the network, the stronger its criticality and the greater its influence. Another measure of node importance is eigenvector centrality. The eigenvector centrality calculates that the influence of the node in network not only depends

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on the number of its neighbour nodes (the number of nodes that the node can affect, that is, the out-degree), but also depends on the influence of neighbour nodes (Liu et al., 2015). The eigenvector centrality is proportional to the influence of neighbour nodes.

Therefore, the paper proposes the integrated project criticality measure (*IPCM*) algorithm, which integrates the location attribute (K-shell), the local attribute (neighbour node analysis) and the global attribute (eigenvector centrality) of the node in the project portfolio network. The *IPCM* algorithm can measure the comprehensive criticality. Furthermore, to analyse the dynamic propagation process of risk in the project portfolio network, the link entropy is defined to measure the propagation influence of the projects in network. And the link entropy is used to measure the propagation influence of project's spreading in the network (Pan et al., 2006).

In terms of project criticality in the portfolio, Ghapanchi et al(2012) proposed a method of portfolio selection based on the Date Envelopment Analysis (*DEA*), considering the uncertainty and dependency relationship; Killen (2017) used the network mapping to analyse the impact of inter-project dependencies on project portfolio selection results; Jafarzadeh et al.(2018) proposed an integrated project portfolio selection model to achieve project priority ranking by analysing the priority criteria, uncertainty and inter-project dependencies; Ghasemi et al. (2018)defined the project risks from the level of the project, project portfolio and inter-project dependencies, and used Bayesian network to realize the project portfolio risk analysis; Neumeie et al. (2018) used the Bayesian to achieve project portfolio prioritization based on the inter-project dependencies and project risks. However, these studies ignore the dynamic propagation of risk in the portfolio network. In the portfolio network, the risk of a project will cause the risk of other projects which are dependent on it, and then the risk source of the project will spread to other projects in the network, which will affect the success of the whole project portfolio.

Overall, we contribute to research in the project criticality using *IPCM* algorithm, link entropy and *SIRF* model. Attempts are also made to build the project portfolio network and measure the propagation influence using *IPCM* algorithm and link entropy. Furthermore, the paper uses the *SIRF* to analyse the criticality of projects in the portfolio considering the risk propagation. The contributions of this paper are summarized as follows:1）From the perspective of risk propagation, the criticality the project portfolio of projects in the portfolio network is analysed; 2） According to the practice of complex R&D projects, the traditional infectious disease model (*SIR*) is extended, and the SIRF model is proposed to analyse the propagation process of risks in the portfolio network ; 3） The *IPCM* algorithm proposed in the paper integrates the local, global and location attributes of nodes in the network, and is used to analyse the criticality the project portfolio of a project on other projects in the portfolio network.

2 MEASURING THE PROPAGATION CRITICALITY THE PROJECT PORTFOLIO OF PROJECTS

2.1 The Project Portfolio Network and Its Comprehensive Criticality

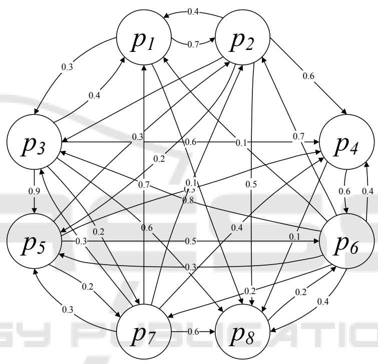

Figure 1: The project portfolio network.

	p_1	p_2	p_3	p_4	p_5	p_6	p_7	p_8
p_1	p_1	.4	.4			.1	.7	
p_2	.7	p_2			.3	.7	.1	.2
p_3	.3		p_3			.8	.3	
p_4		.6	.6	p_4	.3		.4	
p_5		.2	.9		p_5	.3	.3	
p_6				.6	.5	p_6		
p_7	.4		.2		.2	.2	p_7	
p_8	.2	.5	.6	.1		.4	.6	p_8

Figure 2: The DSM description of network.

As shown in Figure 1, the project portfolio network is constructed by taking the project as "node" and the dependency relationship between projects as "edge". The network reflects the direction and strength of the dependency relationship among projects in the portfolio. Further, the project portfolio network can be defined as the design structure matrix (DSM) (Browning, 2016). In the portfolio DSM, the column indicates the dependency of the project on other projects, the row indicates that the project is dependent on other projects, and the non-diagonal number indicates the dependency strength of a project on other projects, as shown in Figure 2.

Further, we use the *IPCM* algorithm to measure the comprehensive criticality of projects in the portfolio. The proposed algorithm in the paper integrates the location (K-shell), local (neighbour node analysis) and the global (eigenvector centrality) attributes of nodes in the network and analyses the degree of influence of a project on other projects in portfolio network. The specific process is as follows: 1) Measuring the importance of projects (*Ks* value) in the network based on the K-shell decomposition method. The *Ks* value reflects the importance of the project's position in the network; 2) Further, based on the calculation of *Ks* value, the influence is defined according to the "neighbour nodes" in the complex network. It analyses the project criticality of projects from the location and local attributes; 3) Using eigenvector centrality to measure the influence of the project in the network from the global attribute; 4) Integrating the analysis results of step 2 and 3, we define an integrated influence measurement model and analyse the comprehensive influence in the portfolio network.

(1) Measuring the criticality based on the K-shell and neighbouring nodes

It can be seen from Figure 1 that the project portfolio network in the paper is a weighted directed graph, so the K-shell decomposition method for undirected weighted network proposed by Garas et al. is extended to directed weighted K-shell (Garas, 2012). The $Ks(p_i)$ is the project criticality using the K-shell decomposition:

$$Ks(p_i) = \left[OD(p_i)^{\alpha} \, PI\_DSM(p_k, p_i)^{\beta} \right]^{\frac{1}{\alpha+\beta}} \qquad (1)$$

where $OD(p_i)$ is the out-degree of project p_i, which is the number of project nodes adjacent to the p_i in the network; $PI\_DSM(p_k, p_i)$ is the dependency strength between project p_i and p_k. The values of α and β are 1 in the paper.

The strength of the dependency relationship between projects in the portfolio network is a decimal between 0 and 1. Therefore, the $Ks(p_i)$ calculated by formula (1) is no longer an integer number. Before using the K-shell algorithm to decompose, the paper performs the following processing on the dependency strength *PI_DSM*, 1) Normalize all the elements in *PI_DSM* based on their average value; 2) Divide the normalized result by its minimum value, and the minimum value in *PI_DSM* is 1;3) The value in *PI_DSM* is processed by rounding down strategy, as shown in Figure3, that is , all the values in *PI_DSM* are rounded down.

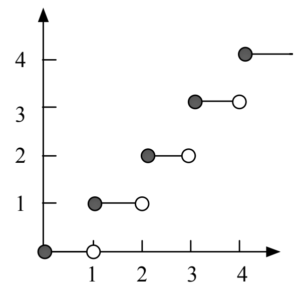

Figure 3: Rounded down graph.

Furthermore, on the basis of calculating the *Ks* value of all projects in the project portfolio network, we measure the criticality using K-shell, as shown in Figure 4. The specific process is:1) Remove all nodes in the network that the degree is 1, as p_1 and p_2 in the Figure 4 (b). After removing the 1-degree nodes, there may be some nodes in the network with only one link, shown as the p_7 in Figure 4 (c). We iteratively remove these nodes until there are nodes with degree 1 in the network, as shown in Figure 4 (d). The removed nodes with *Ks*=1 are considered to be in the first layer of the network; 2) In a similar way, nodes with a degree value≤2 are removed; 3) We continue the process until all the nodes with higher *Ks* values are removed; 4) In the iterative decomposition process, if there are isolated nodes in the network, then we assign 0 to their *Ks* values; 5) Finally, each node in the network is assigned with a *Ks* value. And the network can be seen as a hierarchical structure from the core to edge layer, as shown in Figure 4(a).

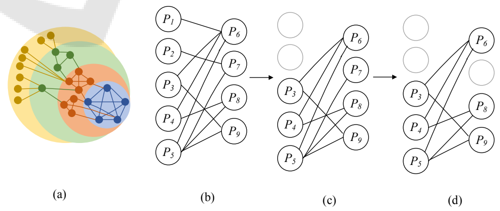

Figure 4: K-shell decomposition process.

Then, define the influence based on the location attributes as shown in formula (2), which is obtained based on the calculation of the *Ks* value.

$$LI(p_i) = \sum_{i \in \Gamma(v)} Ks(p_i) \qquad (2)$$

where the $\Gamma(v)$ is the out-degree neighbour nodes of p_i. $\sum_{i \in \Gamma(v)} Ks(p_i)$ is the sum of *Ks* values of all the out-degree neighbour nodes.

(2) Measuring the project criticality based on eigenvector centrality

We use the eigenvector centrality to measure the influence of the project in portfolio network. Eigenvector centrality holds that the influence of a node in the network depends on not only on the number of its neighbours, but also on the influence of the neighbour nodes it affects (Joyce et al., 2010). The centrality of eigenvector is directly proportional to the influence of the neighbour nodes. Therefore, the higher the influence of a project node in the network, the higher the influence of the project node. The specific calculation is shown in formula (3). The paper defines the influence of the projects using eigenvector as *EI* (p_i),

$$EI(p_i) = x_i = c\sum_{j=1}^{n} a_{ij} x_j \tag{3}$$

where c is a constant. $x = (x_1, x_2, \cdots, x_n)^T$, when the steady state is reached after iterations, it can be written in the following matrix form.

$$R^* = A \times R \tag{4}$$

where A is the dependency matrix between projects and R^* is the eigenvector for the largest eigenvalue of (i.e., principal Eigenvector). The eigenvector R^* is finally normalized by dividing each element in *R* by the sum over all the elements in R^*. The normalized value in *R** determines the project influence in the project portfolio network.

(3) Measuring the comprehensive influence of the project based on the *IPCM*

We measure the comprehensive criticality by integrating the results of $LI(P_i)$ and $EI(P_i)$:

$$CI(p_i) = 1 - \left[1 - LI(p_i)\right] \times \left[1 - EI(p_i)\right] \tag{5}$$

where the *LI* (p_i) is calculated by formular (2) and *EI* (p_i) is calculated by formular (3).

2.2 Measuring the Propagation Influence using the Link Entropy

The link entropy is used to measure the propagation influence of the project in portfolio network, that is, the degree of influence of a certain project on other project in the network after the occurrence of risk is shown in formula (6). The greater the influence of the project in the network, the more likely the risk will affect other projects in the network.

$$LE_{i,j} = -\frac{1}{lnL} CI(p_i) \times \frac{DSM(k,i)}{\sum_{q=1}^{N} DSM(q,i)} ln\left[CI(p_i) \times \frac{DSM(k,i)}{\sum_{q=1}^{N} DSM(q,i)}\right] \tag{6}$$

where *CI* (p_i) is calculated by formular (5), $DSM(k,i) / \sum_{q=1}^{N} DSM(q,i)$ is the ratio of the dependency strength of p_i to p_k to the dependency strength of p_i on all other projects.

3 ANALYZING THE RISK PROPAGATION IN THE PROJECT PORTFOLIO NETWORK BASED ON SIRF MODEL

In the project portfolio network, after a project has a risk, it will make the dependent projects risky, which may cause risk propagation. Based on the *SIRF* model, the paper analyses the propagation process of risk factors in the project portfolio network, and then realizes the project prioritization considering dynamic risk propagation.

3.1 Building the *SIRF* Model

In the traditional *SIR* model, the project has three states: *S*(susceptible) state, which means that the project is vulnerable to the spread of the project risk associated with it in the portfolio network; *I*(infected) state, which means that the risk of the project has occurred; *R*(recovered) state, which means the probability of the risk is within the tolerance ability or the risk is resolved. According to the practice of project portfolio management, the traditional *SIR* model is extended to the *SIRF* model. The project has a *F*(failure) state in the *SIRF* model, which means the project failed. Then, the project and its dependency relationship are removed from the portfolio network. The project portfolio network in the initial state is described as *G*= (*V*, *E*), where *V* is the set of projects, and *E* is the set of inter-project dependency relationship (directed edges between projects). When the project in the *F* state is removed from the portfolio network, the network is described as $G'=\{V', E'\}$, where $V' \subseteq V$, $E' \subseteq E$。 When there are no projects removed from the portfolio network, then $V'= V$, $E' =E$.

Furthermore, the risk of project p_i in the project portfolio network will lead to the risk of other projects which are dependent on it, and then lead to the "domino effect" of risk in the portfolio network. For example, the risk of project p_i will change the state of p_j that is dependent on it. The state of project p_j will change from the S to I state. At the same time, the project node in the I state will be converted to the R or F state. The flow relationship of the process is shown in Figure 5.

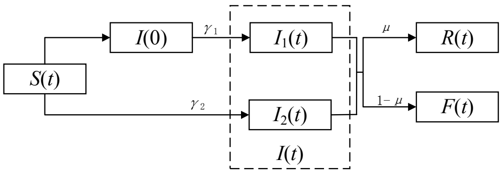

Figure 5: Project state transition due to risk propagation.

3.2 Analysing the Risk Propagation using the *SIRF*

Projects in the R or F state in the portfolio network will no longer be infected again. The probability that the project in the S state will change to the I state under the influence of the dependent project is γ, and the value of γ is determined by the link entropy (equation 6). The project in the I state will change to the R state with the probability of μ, and to the F state with the probability of 1-μ. The value of μ is determined by the project's risk tolerance. The specific calculation process is as follows, if the probability of project p_j in I state at the initial moment is P_j^I (0), then the probability of project p_i changing from S to I state is:

$$P_i^I(0) = 1 - \prod_{j=1}^{N}\left[1 - P_j^I(0) \times LE_{i,j}\right] \quad (7)$$

where the $LE_{i,j}$ is the link entropy from p_j to p_i.

Similarly, it is supposed that the probability of the project p_i in the R state at the initial moment is $P_i^R(0)$, and the probability of the F state is $P_i^F(0)$. Therefore, as shown in Figure 5, the transition relationship between S, I, R and F states of the project p_i is:

$$P_i^R(0) = \mu P_i^I(0) \quad (8)$$

$$P_i^F(0) = (1-\mu) P_i^I(0) \quad (9)$$

Suppose $P_i^S(t)$, $P_i^I(t)$, $P_i^R(t)$ and $P_i^F(t)$ are the probabilities that the project p_i is in the state of S, I, R and F respectively at time t, and , $P_i^S(t+1)$, $P_i^I(t+1)$, $P_i^R(t+1)$ and $P_i^F(t+1)$ are the probability at the time t+1. Therefore, it can be seen from Figure 5 that the iterative process of risk propagation in the portfolio network can be expressed as:

$$P_i^I(t+1) = 1 - \prod_{j=1}^{N}\left[1 - P_j^S(t) \times LE_{i,j}\right] \quad (10)$$

$$P_i^R(t+1) = \mu P_i^I(t) \quad (11)$$

$$P_i^F(t+1) = (1-\mu) P_i^I(t) \quad (12)$$

We can get the probability that the projects in the portfolio network will be in S, I, R and F at any time form formular (10)-(12). When the number of iterations in infinite, the probability matrix P will tend to be stable, so a stable probability value can be obtained. Also, the sum of probabilities of the project in S, I, R and F is 1.

$$P_i^{(S)}(t) + P_i^{(I)}(t) + P_i^{(R)}(t) + P_i^{(F)}(t) = 1 \quad (13)$$

3.3 Using SIRF for Ranking the Projects in the Portfolio

To quantitatively analyse the propagation process of risk in the portfolio network, we define the indicator of spreading influence strength (*SIS*). The *SIS* refers to the final infection scale of the project p_i have a risk in the network. It is the sum of the probability of all project risks that can eventually be infected by project p_i, that is, it includes the neighbour nodes directly infected by project p_i, and the nodes that can be transmitted form the project infected by project p_i as the intermediary. In the project portfolio network, the probability P_i in the risk state is determined by the sum of the stable probabilities of the project in the I and F state. Therefore, the spreading influence strength (*SIS*) of p_i can be calculated as:

$$SIS_i = \sum_{j \in A} P_j = \sum_{j \in A} P_j^I(\infty) + P_j^F(\infty) \quad (14)$$

where the set A is all the projects infected by the project p_i.

Totally, the criticality of projects in the portfolio network considering the risk propagation can be defined as the proportion of the spreading influence strength (*SIS*) of p_i to the sum of the spreading influence strength (*SIS*) of all projects in the project portfolio network.

$$PC_i = \frac{SIS_i}{\sum_{j \in PP} SIS_j} \quad (15)$$

where PP is the set of all projects in the portfolio.

4 AN ILLUSTRATIVE EXAMPLE

Taking the project portfolio of an aviation equipment of R&D enterprise as an example, the paper conducted a laboratory experiment to priority the project in the portfolio considering the dynamic propagation of risks. The company's R&D project portfolio contains 10 projects, and the dependency relationship between these projects is described based on DSM as shown in Figure 6, and the link entropy between projects measured using equation 6 is as shown in Figure 7.

	p_1	p_2	p_3	p_4	p_5	p_6	p_7	p_8	p_9	p_{10}
p_1	p_1	.6	.4		.5	.1	.4	.7	.4	.6
p_2	.3	p_2	.1	.2		.7	.5		.2	
p_3	.1		p_3	.5	.5			.1	.3	.3
p_4			.3	p_4	.1		.8		.1	.6
p_5			.1	.3	p_5	.2	.1		.1	.5
p_6			.6	.2	.1	p_6	.2	.2	.8	.1
p_7	.4			.1	.3	.6	p_7		.4	
p_8	.2	.3	.5		.2			p_8	.3	
p_9					.6	.4	.3	.3	p_9	.3
p_{10}		.5	.4	.3	.7			.1	.5	p_{10}

Figure 6: the dependency relationship between projects.

	p_1	p_2	p_3	p_4	p_5	p_6	p_7	p_8	p_9	p_{10}
p_1	p_1	.31	.25		.06	.25	.28	.49	.2	.27
p_2	.47	p_2	.09	.22	.11	.21	.07		.12	
p_3	.23		p_3	.4	.22	.23		.13	.16	.16
p_4			.2	p_4	.15	.21	.12		.35	.27
p_5			.09	.29	p_5	.23	.07		.2	.24
p_6			.33	.22	.32	p_6	.17	.21	.32	.35
p_7				.13	.15	.18	p_7		.2	
p_8	.37	.19	.29		.11	.25	.31	p_8	.16	
p_9					.33	.25	.17	.28	p_9	.33
p_{10}		.27	.25	.29	.27	.25	21	.13	.23	p_{10}

Figure 7: the link entropy between projects.

The probability that the project in the *S*, *I*, *R* and *F* in a stable state obtained by the analysis of *SIRF* model is shown in Figure 8(a). Furthermore, the scores of importance are shown in Figure 8(b) by using equations (14) and (15). Therefore, the priority ranking that project manager should pay attention to is P_1-P_6-P_{10}-P_8-P_3-P_9-P_4-P_2-P_5-P_7, when the project manager is considering the risk dynamic propagation.

	PS	*PI*	*PR*	*PF*
p_1	.3	.41	.09	.21
p_2	.36	.27	.11	.26
p_3	.34	.31	.1	.24
p_4	.36	.28	.1	.25
p_5	.38	.23	.11	27
p_6	.3	.4	.09	.21
p_7	.43	.14	.13	.3
p_8	.32	.35	.09	.23
p_9	.36	.28	.11	.25
p_{10}	.31	.39	.09	.21

	PC
p_1	.703
p_2	.636
p_3	.657
p_4	.640
p_5	.617
p_6	.701
p_7	.571
p_8	.675
p_9	.64
p_{10}	.694

(a) The output of SIRF (b) The scores of importance

Figure 8: The results of portfolio risk analysis.

$$p_s = 1 - \frac{6\sum_{i=1}^{n} d_i^2}{n(n^2-1)} \tag{16}$$

where the *n* is the number of projects in the portfolio, d_i is the difference of criticality ranking of each project in the portfolio under different measurement conditions.

Furthermore, the Spearman correlation coefficient is calculated to measure the consistency between criticality ranking and actual ranking results, as shown in Table 1. It can be seen from the table 1 that the project criticality ranking results obtained in the paper based on the integrated project criticality measure (IPCM) algorithm and SIRF model have the highest consistency with the actual results. Furthermore, the eigenvector centrality is second, and eigenvector centrality measures the relative importance of projects based on neighbour nodes. The results can also reflect the relative importance of projects better with the position of the project in the network ignored. However, the ranking results based only the location attribute without considering the propagation attribute have a large deviation from the actual situation. In conclusion, the *IPCM* algorithm proposed in this paper can analyse the relative importance of the project's location, local and global attributes in the portfolio network. At the same time, the project criticality ranking results obtained based on the *SIRF* model considering the dynamic propagation of risks are in the highest agreement with reality. Therefore, the project's location, local and global attributes should be integrated when analysing the criticality of projects in the portfolio. The absence of any analysis element will cause project criticality deviating from the actual situation.

Table 1: The consistency results of using Spearman correlation coefficient.

	K-shell	Eigenvector centrality	IPCM	IPCM & SIRF
Spearman correlation coefficient	-0.309	0.939	0.867	0.952

Therefore, we propose the integrated project criticality measure (IPCM) to measure the comprehensive influence of the projects in the portfolio network. It has the highest consistency with the actual situation.

4 CONCLUSIONS

To analyse the criticality of projects in the portfolio considering dynamic risk propagation, the paper proposes the integrated project criticality measurement (IPCM), and the algorithm is divided into 4 steps, 1) Using the K-shell to analyse the criticality based on the location attributes; 2) Analysing the project's impact based on the neighbour nodes in the complex network; 3) Measuring the project's impact using the eigenvector centrality; 4) Integrating the calculation results of the above to construct a measurement model of the project's comprehensive influence. Furthermore, link entropy is used to measure the propagation influence of project's spreading in the network. Furthermore, combined with the practice of R&D project management, the traditional *SIR* model is extended to the *SIRF* model. The paper considers that there is a *F*(failure) state in the project portfolio network, which means that the project has failed. Finally, the *SIRF* model is used to analyse the dynamic propagation process of risks in the project portfolio network, and the priority ranking is realized under the risk dynamic propagation.

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