Structure Modeling and Key Node Analysis of Equipment Development Project Based on Hyper-Network

Qunyou Qian[1,a] , Qingsong Zhao*[1,b] , Kaifang Wu[2,c] , Qihong Chen[1,d]

[1]National University of Defense Technology, Changsha, China
[2]Shanghai Institute of Mechanical and Electrical Engineering, Shanghai, China

[a]957262167@qq.com, [b]zhaoqingsong@nudt.edu.cn,
[c]504679173@qq.com, [d]chenqihong16@nudt.edu.cn

Abstract. The equipment development stage involves multiple project organizations and tasks simultaneously. These entities can impact each other, leading to conflicts and risks related to resources and schedules. As our national defense system rapidly modernizes, the scale and complexity of these relationships become more apparent, resulting in increased uncertainty and management challenges during the equipment development stage. Therefore, it is crucial to analyze the key elements of equipment development projects, construct a network model based on these elements, and conduct critical path analysis. This study focuses on three crucial elements: project tasks, project organizations, and project resources. By constructing a hyper-network model based on these elements and their relationships, it becomes possible to address practical challenges during the equipment development phase and provide support for project management in our military.

Keywords: equipment development project management, hyper-network, key node analysis

1 Introduction

With the rapid development of China's defense system and military strength, equipment procurement is no longer limited to small-scale and single-structure projects. Meanwhile, advanced military theories such as mosaic warfare [1] and distributed warfare [2] have further increased the scale and complexity of equipment development. As a result, accurately identifying key tasks, organizations, and resources is crucial for effective management of work, resources, and task schedules.

With the continuous development of project management, scholars from various countries have made various improvements to the increasingly complex development projects. Qing Yang proposed a batch-based agile project management method, which combines parallel engineering with agile methods to solve problems in the practice of multi-project parallel development [3]. Amira Sharon studied the potential benefits of using design structure matrix in the context of model-based systems engineering, in order to improve project integration and management [4]. Chinese scholar Shujun Yang

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analyzed the use of big data in the research of anti-aircraft weapon equipment and proposed corresponding suggestions and strategies [5]. J. Baschin proposed a method to support project leaders in selecting and tailoring project management methods and processes for diverse modern mechanical engineering product development projects [6]. In the analysis of key milestones based on the equipment development project model, common methods include Critical Path Method (CPM) and Program Evaluation and Review Technique (PERT) developed by the US military, which identify the ”critical path” and ”critical nodes” through the topological structure of the network diagram.

However, as the scale of equipment development projects rapidly increases, traditional project management models are gradually showing their shortcomings. For instance, while the Critical Path Method (CPM) provides simple and feasible results, it neglects the uncertainty of the development process, often resulting in project delays and resource wastage [7]. On the other hand, the IDEF3 method focuses excessively on depicting the process of project development, making the modeling process cumbersome and not conducive to further analysis of key nodes [8]. Therefore, it is necessary to study and explore new models and methods suitable for analyzing key nodes in equipment development projects.

With the deepening research on networks, scholars have discovered that modeling and analysis of hyper-networks can reveal the topological structure and dynamic evolution mechanism of network systems. By constructing hyper-networks for equipment development projects, it can provide a clear and intuitive understanding of the complex and heavy work involved in equipment development projects today. Therefore, this paper proposes to use the hyper-network model to model the equipment development project and analyze the key node of the equipment development project.

2 Equipment Development Project Structure Analysis

Equipment development projects are essentially multidimensional systems, and the first step in modeling them is to have a clear understanding of their structure. The elements of equipment development projects can be divided into three main categories based on their functional characteristics: project tasks, project organization, and project resources. The relationships in equipment development projects include inter-organizational relationships, inter-task relationships, inter-resource relationships, organizational-task relationships, and resource-task relationships. Before constructing a hyper-network model, it is necessary to analyze the elements and their relationships.

2.1 Equipment Development Project Elements

1) Project organization: Project organization in equipment development projects refers to the units that have technical personnel and administrative management institutions. They ensure that project objectives are achieved on time and with the desired quality through planning, organizing, monitoring, and other means.

2) Project tasks: project task is the concrete decomposition of the project development work, which requires a certain amount of project resources such as time and funds, and is the basis for a series of work and activities.

3) Project resources: Project resources refer to all the objective existence with use value in the process of project development. The types and amounts of resources required for different tasks vary.

2.2 Interrelationship Between Elements of Equipment Development Projects

1) Interrelationships between project tasks: There is an objective chronological logical relationship between project tasks. That is, there is a chronological relationship between project tasks in an equipment acquisition and development project.

2) Interrelationships among project organizations: In equipment development projects, the common inter-organizational relations include affiliation, cooperation, competition and information transfer.

3) Interrelationships among project resources: There are replaceable relationships among project resources. For example, in order to complete a certain project task, the scarcity of human resources can be overcome by task outsourcing or personnel hiring with sufficient funds. It is worth pointing out that this relationship may continue to disappear and form as the project progresses.

4) Interrelationship between project organization and project tasks: In equipment development projects, the relationship between the organization and the task is assistance, approval, and execution.

5) Interrelationship between project resources and project tasks: The relationship between project tasks and project resources is the relationship between use and being used.

3 Equipment Development Project Hyper-Network Model Construction

3.1 Constructive Thinking

Hyper-network, also known as the network of networks. In terms of structure, hyper-network is composed of many functional networks with different properties and the relationships between networks. Therefore, according to the analysis of the structure of equipment development projects in Chapter 2, this paper mainly constructs five networks: project tasks, project organization, project resources, organizational-task interactions, and resource-task interactions.

3.2 Network Modeling

1)Modeling of project task networks: Define the project task network as $PTN = (V_{ptn}, E_{ptn})$, the project task set as $V_{ptn} = (a_1, a_2, \ldots, a_N)$, the project task as $a_i =$

$(t_i, \omega_i, \sigma_i)$, t_i denotes the normal time required to perform the project task a_i, ω_i is the organizational paralysis penalty factor for the project task a_i. Define that when all the project organizations involved in project task a_i are paralyzed due to factors such as poor management ability, decision-making errors, etc., project Task a_i will take ω_i times more normal time t_i to complete. σ_i is the resource scarcity penalty factor of project task a_i. Define that when all project resources involved in project task a_i are scarce due to supply breakdown, low reserve capacity, etc., project task a_i will take σ_i times more normal time t_i to complete. Define the adjacency matrix as $E_{ptn} = \{a_{ij} | (a_i, a_j), 1 \leq i, j \leq N\}$, which indicates the timing logic relationship between tasks, a_{ij} is 1 when project task a_i is the immediately preceding task of project task a_j , otherwise it is 0. Define $d_i^{pre} = \sum_{k=1}^{N} a_{kj}$ to indicate the number of immediately preceding tasks of project task a_i and define $d_i^{smc} = \sum_{j=1}^{N} a_{ij}$ to indicate the number of immediately following tasks of project task a_i.

2)Modeling of project organization networks: Define the project organization network as $PON = (V_{pon}, E_{pon})$. Define the set of project organizations as $V_{pon} = (o_1, o_2, \ldots, o_M)$. Define p_{o_i} as the probability that the project organization o_i will be crippled by factors such as poor management skills and poor decision making. Define the adjacency matrix as $E_{pon} = \{o_{ij} | (o_i, o_j), 1 \leq i, j \leq M\}$, which indicates the hierarchical affiliation between organizations, when the project organization o_j is the subordinate organization of the project o_i , $o_{ij} = 1$.

3)Modeling of project task-organization interaction networks: Define project tasks-organizing interaction networks as $PTON = (V_{pton}, E_{pton})$. Define the set of network nodes as $V_{pton} = (V_{ptn} \cup V_{pon})$. Define the adjacency weighting matrix as $E_{pton} = \{AO_{ij} | 1 \leq i \leq N, 1 \leq j \leq M\}$ to represent the relationship between the organization and the task, there are various relationships between the project organization and the project task, such as approving, assisting, leading, etc. The weights of different relationships are different, and AO_{ij} is defined to represent the weight of the relationship between the task a_i and the organization o_j . At the same time, it also indicates the degree of influence of the organization on the task execution process

4)Modeling of the project resource network: Define the project resource network as $PRN = (V_{prn}, E_{prn})$ and define p_{r_i} as the probability that a project resource r_i will become scarce due to low reserve capacity, supply disruptions, etc. Define the set of network nodes as $V_{prn} = (r_1, r_2, \ldots, r_Q)$. Define the adjacency matrix as $E_{prn} = \{b_{ij} | (b_i, b_j), 1 \leq i, j \leq Q\}$ to denote the substitutable relationship between resources, and b_{ij} is 1 when the project resource b_i can replace the project resource b_j, and 0 otherwise.

5)Modeling of project task-resource interaction networks: Define the project task-resource network as $PTRN = (V_{ptrn}, E_{ptrn})$. Define the network node set as $V_{ptrn} = (V_{ptn} \cup V_{prn})$. Define the adjacency weighting matrix as $E_{ptrn} = \{AR_{ij} | 1 \leq i \leq N, 1 \leq j \leq Q\}$ indicates the relationship between the group resources and tasks, and the weight of different relationships is different. The provisions of the AR_{ij} indicates the task of the a_i and the resources of the r_j relationship of the weights.

4 Analysis of Key Nodes of Equipment Development Project Based on Hyper-Network Modeling

4.1 Hyper-Network-Based Analysis of Mission-Critical Nodes

1)Analytical thinking: Research and development projects involve a large number of project tasks and complex relation- ships. Traditional project management theory by analyzing the critical path, and network index analysis through the nodes of the network index value to determine the critical nodes. When analyzing the key nodes of the equipment development project, it can not be judged solely by the network index value, nor can it be judged directly by the traditional project management theory. Because part of the network index value of the higher nodes are not in the project task critical path. And in the critical path judged by traditional project management theory, there are also nodes whose network index value is not ideal. Therefore, in the project task critical node analysis, this paper first judges the critical path of the equipment development project, and judges the nodes on the critical path according to the network index value. For the nodes on the non-critical path, this paper mainly adopts the method of sensitivity analysis to judge.

2)Selection of network indicator values: Network metrics can reflect the importance of nodes in the network topology, however, when utilizing network metric values for the analysis of important nodes in an equipment development project, it is important to first clarify the practical significance of the selected network metric values in the project. Degree value is a measure of the number of node edges in the network structure of the numerical value, in the equipment project development task network, the higher the in-degree of the node, the more tasks before the task, and the higher the out- degree of the node, the more tasks after the task. Obviously, the degree value can effectively reflect the importance of the project task node. In the task network, the betweenness reflects the role and influence of the task in the whole network, the larger the betweenness of the node, the greater the probability that it is in more feasible execution paths of the task, and the stronger the impact on the smooth implementation of the entire project, so the node betweenness number of the node can also reflect the importance of the project task nodes. Therefore, in this paper, when choosing the network index value to judge the key nodes, the three network index values of in-degree, out-degree and betweenness are chosen to make a comprehensive judgment.

3)Sensitivity analysis of non-critical path nodes: In the equipment development project task network, in addition to the nodes on the critical path, there are a large number of non-critical path nodes, purely by the size of the network index value judgment is not applicable. This paper mainly uses the method of sensitivity analysis to judge, the steps are as follows: Firstly, determine the critical path based on the CPM method to determine the total time for project completion T. Secondly, filter non-critical path nodes based on the values of network metrics such as in-degree, out-degree, betweenness, etc. Then Set the interference value Δt. Next, for filtered non-critical path nodes, increase the interference value by the completion time of each task and calculate the total project completion time after increasing the disturbance value at each node T' .

Finally, calculate the increase in project completion time after increasing the disturbance value for each node as $\Delta T = T' - T$ and compare the filtered non-critical nodes with ΔT, whose increasing value indicates that the node is more critical.

4.2 Hyper-Network-Based Analysis of Key Organizational Nodes

1) Analyzing ideas: Equipment development projects involve a wide range of organizations, the relationship between organizations and tasks is complex and diverse, in the analysis of key organizational nodes need to be based on the relationship between the project organization and project tasks. Therefore, in the analysis of key nodes of the project organization, this paper first constructs the project task collaboration network of the organization based on the project organization- project task interaction network. By analyzing the network index value of each organization node in this project task collaboration network, the project organization node with ideal network index value is screened. However, the equipment development project is a dynamic process, with the development project, some organizations due to the completion of the project tasks involved in the withdrawal at the same time there are some organizations involved in the project tasks, therefore, the importance of the project organization nodes will continue to change as the project is carried out. According to the adjacency weighting matrix in the project organization-task interaction network, the meaning of the importance of the project organization nodes is specified, so as to analyze the change of the importance of the screening nodes during the whole project process. However, according to the above method, although it can analyze the key nodes at different moments, this method still has limitations and fails to analyze the key nodes in the dimension of the whole process of the equipment development project, therefore, this paper considers the case of paralysis of the organizational nodes to carry out the analysis of the key project organizational nodes.

2) Definition of Organizational Node Importance: For the same project task, different project organizations involved in the task play different role positions, such as approval, supporting, leading, etc., and different weights are assigned according to these different role positions. The weight of the relationship between the project task a_i and the project organization o_j is

$$AO_{ij} = \left\{ \begin{array}{ll} weight_1, & role_1 \\ weight_2, & role_2 \\ \dots & \dots \\ weight_n, & role_n \\ 0, & \text{h}ave\ not\ participated \end{array} \right\}$$

Define $E_t = \left\{ \varepsilon_{ij}^{t} | 1 \le i \le N, 1 \le j \le M \right\}$ that reflects the involvement of the project organization nodes in the project tasks at moment t. ε_{ij}^{t} is 1 means that project organization j is involved in the project task i at moment t, and a value of 0 means that it is not involved. Therefore, define the node importance of the project organization node j at the time of t as $W_j^t = \sum_i AO_{ij} \cdot \varepsilon_{ij}^{t}$.

3) Analysis of key organizational nodes considering organizational node paralysis: During the course of an equipment development project, the project organization may be paralyzed by various risk factors, such as low management capacity and poor decision-making, which in turn affects the associated project organization and the individual project tasks in which it is involved, and ultimately leads to an increase in the overall project duration. From the definitions of the probability of organization paralysis and the task penalty factor in Chapter 3, the completion time of project task i can be obtained considering the paralysis of project organization j.

$$t_i' = (1 + \omega_i \cdot \frac{p_{o_j} \cdot AO_{ij}}{\sum_{j=1}^{M} AO_{ij}}) t_j$$

Sequentially analyze the completion time of all project tasks under the paralysis of the project organization node j, and get the total completion time of the equipment development project as $T' = \sum_i t_i{}'$. Then calculate the total project completion time increase value under the paralysis of project organization node j as $\Delta T = T^{'} - T$. and analyze the total project completion time increase value under the paralysis of all screened project organization nodes, the larger the value is, the more important the impact of the paralysis of the project organization node on the implementation of the entire project, by virtue of it we can determine the key project organization nodes.

4.3 Hyper-Network-Based Analysis of Key Resource Nodes

1) Analyzing ideas: The analysis idea of key resource nodes is similar to that of organization nodes, however, since the number of project resource types is much less than the number of project organizations, there is no need to screen them first when conducting the analysis, and it is possible to directly conduct the analysis of the importance of resource nodes, so as to analyze the change in the importance of the whole process of each project resource project. In order to analyze the key nodes of each resource in the whole process of the equipment development project, the scarcity of resources can also be considered in order to carry out the analysis of key project resource nodes.

2) Resource node importance definition: The same project task has different demands on different project resources, this paper takes a qualitative analysis approach to categorize the relationship between project resources and project tasks according to the degree of demand. And give these relationships different weights. The weight of the relationship between the project tasks a_i and the project resources r_j is

$$AR_{ij} = \begin{Bmatrix} weight_1{}', & role_1 \\ weight_2{}', & role_2 \\ \cdots & \cdots \\ weight_{\mathrm{n}}{}', & role_n \\ 0, & \mathrm{h}ave\ not\ participated \end{Bmatrix}$$

Define the adjacency matrix as $E_t = \{\varepsilon_{ij}^t | 1 \le i \le N, 1 \le j \le Q\}$ that reflects the involvement of the project resource nodes in the project tasks at moment t. ε_{ij}^t is 1 means that project resources j are involved in the project task i at t moment, and a value of 0 means that it is not involved. Therefore, define the node importance of the project resource node j at the time of t as $W_j^t = \sum_i AR_{ij} \cdot \varepsilon_{ij}^t$.

3)Analysis of key resource nodes considering resource node scarcity: During the course of an equipment development project, project resources may become scarce due to various risk factors, such as low reserve capacity and supply disruptions, which in turn affects the individual project tasks in which they are involved and ultimately leads to an increase in the overall project duration. From the definitions of the probability of resource scarcity and the resource scarcity penalty factor in Chapter 3, the completion time of project task i can be obtained considering the scarcity of project resources j.

$$t_i^{'} = (1 + \omega_i \cdot \frac{p_{r_j} \cdot AR_{ij}}{\sum_{j=1}^{M} AR_{ij}})t_j$$

Sequentially analyzing the completion time of all project tasks under the scarcity of the project resource node j, the total completion time of the equipment development project was obtained as $T^{'} = \sum_i t_i^{'}$. Calculate the total project completion time increase value under the scarcity of the project resource node j as $\Delta T = T^{'} - T$. Then analyze all the project resource node paralysis under the project total completion time increase value, the larger the value is, the more important the impact of the scarcity of the project resource node on the implementation of the entire project, by virtue of it we can determine the key project resource node.

5 Example Studies

This paper takes the aerospace equipment development project A as an example, analyzes the project structure, constructs the hyper network model, and on the basis of the model, applies the methods studied in this paper to analyze the key project task nodes as well as the project organization nodes respectively, to demonstrate the feasibility of the research methods in this paper.

5.1 Analysis of Project Structure

1) Project tasks: Aerospace equipment development project A mainly includes five stages: feasibility demonstration, program, prototype, and finalization, consisting of a total of 35 tasks, as shown in Figure 1. The project tasks in the above phases are closely linked and there is a clear chronological logic.

2) Project organization: In the equipment development project, according to the different functions of the need for the existence of various types of project organizations. There are subordinate relationships between project organizations.

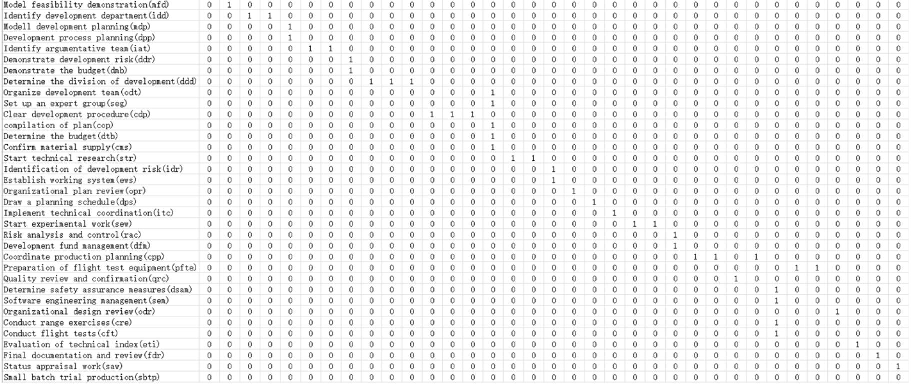
3) Relationship between project organization and project tasks: In equipment development projects A, the relationship that exists between the organization and the task can be divided into three main categories: assisting, leading and approving.

4) Project resources: The project resources involved in an equipment development project A mainly include manpower, space, facilities, funds, technology, materials, and instrumentation. There may be substitutable relationships between re- sources as the project tasks progress.

5) Relationship of project resources to project tasks: In the case of equipment development project A, the relationship between project tasks and project resources is a demand relationship, and the weight of each relationship varies according to the degree of demand.

5.2 Hyper-Network Modeling for Equipment Development Project A

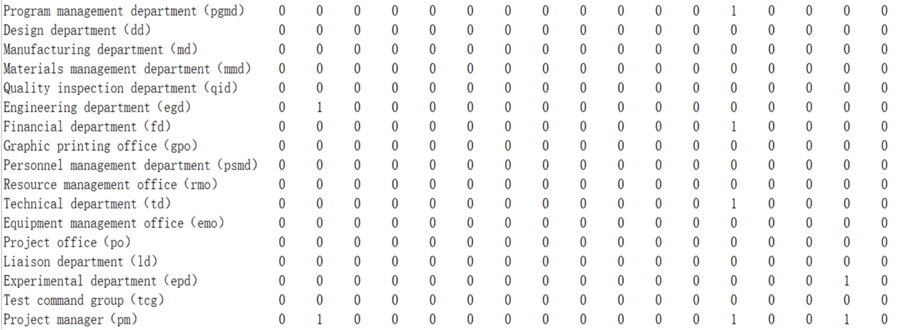
1) Project Task Network: Based on the project task network model $PTN = (V_{ptn}, E_{ptn})$ constructed in Chapter 2, the task set of the A equipment development project is denoted as $V_{ptn} = (a_1, a_2, \ldots, a_{35})$ and the A equipment development project tasks are denoted as $a_i = (t_i, \omega_i, \sigma_i)$. According to the temporal logical relationship between project tasks demonstrated in the project task network plan diagram, the adjacency matrix E_{ptn} is constructed as shown in Fig. 1.



	mfd	idd	mdp	dpp	iat	ddr	dmb	ddd	odt	seg	cdp	cop	dtb	cms	str	idr	ews	opr	dps	itc	sew	rac	dfm	cpp	pfte	qrc	dsam	sem	odr	cre	cft	eti	fdr	saw	sbtp
Model feasibility demonstration(mfd)	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Identify development department(idd)	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Modell development planning(mdp)	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Development process planning(dpp)	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Identify argumentative team(iat)	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Demonstrate development risk(ddr)	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Demonstrate the budget(dmb)	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Determine the division of development(ddd)	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Organize development team(odt)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Set up an expert group(seg)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Clear development procedure(cdp)	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
compilation of plan(cop)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Determine the budget(dtb)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Confirm material supply(cms)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Start technical research(str)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Identification of development risk(idr)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Establish working system(ews)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Organizational plan review(opr)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Draw a planning schedule(dps)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Implement technical coordination(itc)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Start experimental work(sew)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0
Risk analysis and control(rac)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
Development fund management(dfm)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
Coordinate production planning(cpp)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	1	0	0	0	0	0	0	0
Preparation of flight test equipment(pfte)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0
Quality review and confirmation(qrc)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Determine safety assurance measures(dsam)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Software engineering management(sem)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Organizational design review(odr)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
Conduct range exercises(cre)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Conduct flight tests(cft)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Evaluation of technical index(eti)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Final documentation and review(fdr)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
Status appraisal work(saw)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Small batch trial production(sbtp)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Fig. 1. Project task network adjacency matrix

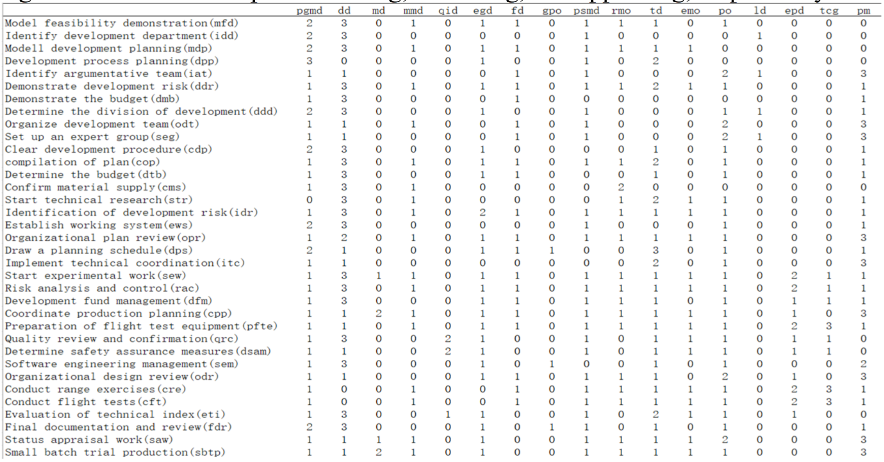
2) Project organization network: Based on the project organization network model $PON = (V_{pon}, E_{pon})$ constructed in chapter 2, the task set of equipment development project A is $V_{pon} = (o_1, o_2, \ldots, o_{17})$. Figure 2 shows the Project organization membership adjacency matrix E_{pon}.



	pgmd	dd	md	mmd	qid	egd	fd	gpo	psmd	rmo	td	emo	po	ld	epd	tcg	pm
Program management department (pgmd)	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Design department (dd)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Manufacturing department (md)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Materials management department (mmd)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Quality inspection department (qid)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Engineering department (egd)	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Financial department (fd)	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Graphic printing office (gpo)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Personnel management department (psmd)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Resource management office (rmo)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Technical department (td)	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Equipment management office (emo)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Project office (po)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Liaison department (ld)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Experimental department (epd)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
Test command group (tcg)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Project manager (pm)	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0

Fig. 2. Project organization membership adjacency matrix

3) Project task-organization interaction networks: Based on the project task-organization network model $PTON = (V_{pton}, E_{pton})$ constructed in chapter 2, note that the set of network nodes is $V_{pton} = (V_{ptn} \cup V_{pon}) = (a_1, a_2, \ldots, a_{35}, o_1, o_2, \ldots, o_{17})$. Then an adjacency weighting matrix E_{pton} can be constructed from the relationships between organizations and tasks as shown in Figure 3. Where 1, 2, and 3 represent the weights of the relationships of assisting, executing, and approving, respectively.

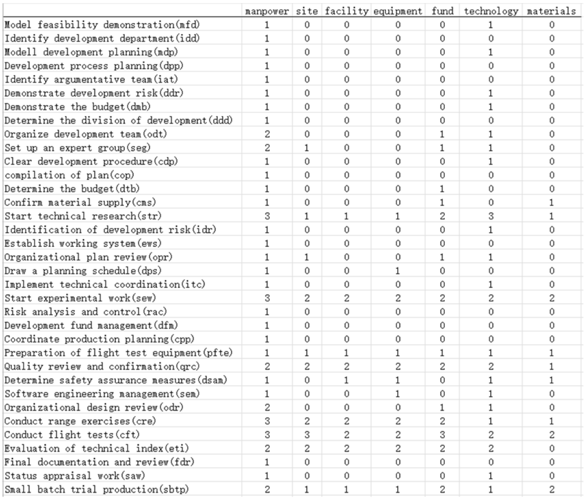


	pgmd	dd	md	mmd	qid	egd	fd	gpo	psmd	rmo	td	emo	po	ld	epd	tcg	pm
Model feasibility demonstration(mfd)	2	3	0	1	0	1	1	0	1	1	1	0	1	0	0	0	0
Identify development department(idd)	2	3	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0
Modell development planning(mdp)	2	3	0	1	0	1	1	0	1	1	1	1	0	0	0	0	0
Development process planning(dpp)	3	0	0	0	0	1	0	0	1	0	2	0	0	0	0	0	0
Identify argumentative team(iat)	1	1	0	0	0	0	1	0	1	0	0	0	2	1	0	0	3
Demonstrate development risk(ddr)	1	3	0	1	0	1	1	0	1	1	2	1	1	0	0	0	1
Demonstrate the budget(dmb)	1	3	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1
Determine the division of development(ddd)	2	3	0	0	0	1	0	0	1	0	0	0	1	1	0	0	1
Organize development team(odt)	1	1	0	1	0	0	1	0	1	0	0	0	2	0	0	0	3
Set up an expert group(seg)	1	1	0	0	0	0	1	0	1	0	0	0	2	1	0	0	3
Clear development procedure(cdp)	2	3	0	0	0	1	0	0	0	0	1	0	1	0	0	0	1
compilation of plan(cop)	1	3	0	1	0	1	1	0	1	1	2	0	1	0	0	0	1
Determine the budget(dtb)	1	3	0	0	0	1	1	0	0	0	1	0	1	0	0	0	1
Confirm material supply(cms)	1	3	0	1	0	0	0	0	0	2	0	0	0	0	0	0	0
Start technical research(str)	0	3	0	1	0	0	0	0	0	1	2	1	1	0	0	0	1
Identification of development risk(idr)	1	3	0	1	0	2	1	0	1	1	1	1	1	0	0	0	1
Establish working system(ews)	2	3	0	0	0	0	0	0	1	0	0	0	1	0	0	0	1
Organizational plan review(opr)	1	2	0	1	0	1	1	0	1	1	1	1	1	0	0	0	3
Draw a planning schedule(dps)	2	1	0	0	0	1	1	1	0	0	3	0	1	0	0	0	1
Implement technical coordination(itc)	1	1	0	0	0	0	0	0	0	0	2	0	1	0	0	0	3
Start experimental work(sew)	1	3	1	1	0	1	1	0	1	1	1	1	1	0	2	1	1
Risk analysis and control(rac)	1	3	0	1	0	1	1	0	1	1	1	1	1	0	2	1	1
Development fund management(dfm)	1	3	0	0	0	1	1	0	1	1	1	0	1	0	1	1	1
Coordinate production planning(cpp)	1	1	2	1	0	1	1	0	1	1	1	1	1	0	1	0	3
Preparation of flight test equipment(pfte)	1	1	0	1	0	1	1	0	1	1	1	1	1	0	2	3	1
Quality review and confirmation(qrc)	1	3	0	0	2	1	0	0	1	0	1	1	1	0	1	1	0
Determine safety assurance measures(dsam)	1	1	0	0	2	1	0	0	1	0	1	1	1	0	1	1	0
Software engineering management(sem)	1	3	0	0	0	1	0	1	0	0	1	0	1	0	0	0	2
Organizational design review(odr)	1	1	0	0	0	1	1	0	1	1	1	0	2	0	1	0	3
Conduct range exercises(cre)	1	0	0	1	0	0	1	0	1	1	1	1	1	0	2	3	1
Conduct flight tests(cft)	1	0	0	1	0	0	1	0	1	1	1	1	1	0	2	3	1
Evaluation of technical index(eti)	1	3	0	0	1	1	0	0	1	0	2	1	1	0	1	0	0
Final documentation and review(fdr)	2	3	0	0	0	1	0	1	1	0	1	0	1	0	0	0	1
Status appraisal work(saw)	1	1	1	1	0	1	0	0	1	1	1	1	2	0	0	0	3
Small batch trial production(sbtp)	1	1	2	1	0	1	0	0	1	1	1	1	1	0	0	0	3

Fig. 3. Adjacency matrix of project organization and inter-task relationships

4) Project Resource Network: Based on the project re- source network model $PRN = (V_{prn}, E_{prn})$ constructed in Section 2, the set of project resources for the development of equipment A is denoted as $V_{prn} = (r_1, r_2, \ldots, r_7)$ and the matrix of substitutable relationships between the resources is denoted as E_{prn}. As project tasks are completed and new tasks are undertaken, the relationships between project resources may change and the matrix of substitutable relationships changes.

5) Project task-resource interaction network: Based on the project task-resource network model $PTRN = (V_{ptrn}, E_{ptrn})$ constructed in chapter 2, note that the set of network nodes is $V_{ptrn} = (V_{ptn} \cup V_{prn}) = (a_1, a_2, \ldots, a_{35}, r_1, r_2, \ldots, r_7)$. Then the adjacency weighting matrix E_{ptrn} can be constructed from the relationship between tasks and resources, which is shown in Fig. 4. It's worth noting that 0, 1, 2, 3 represent the weights of four levels of need: no need, little need, normal need and a lot of need, respectively.



	manpower	site	facility	equipment	fund	technology	materials
Model feasibility demonstration(mfd)	1	0	0	0	0	1	0
Identify development department(idd)	1	0	0	0	0	0	0
Modell development planning(mdp)	1	0	0	0	0	1	0
Development process planning(dpp)	1	0	0	0	0	0	0
Identify argumentative team(iat)	1	0	0	0	0	0	0
Demonstrate development risk(ddr)	1	0	0	0	0	1	0
Demonstrate the budget(dmb)	1	0	0	0	0	1	0
Determine the division of development(ddd)	1	0	0	0	0	0	0
Organize development team(odt)	2	0	0	0	1	1	0
Set up an expert group(seg)	2	1	0	0	1	1	0
Clear development procedure(cdp)	1	0	0	0	0	1	0
compilation of plan(cop)	1	0	0	0	0	0	0
Determine the budget(dtb)	1	0	0	0	1	0	0
Confirm material supply(cms)	1	0	0	0	1	0	1
Start technical research(str)	3	1	1	1	2	3	1
Identification of development risk(idr)	1	0	0	0	0	1	0
Establish working system(ews)	1	0	0	0	0	0	0
Organizational plan review(opr)	1	1	0	0	1	1	0
Draw a planning schedule(dps)	1	0	0	1	0	0	0
Implement technical coordination(itc)	1	0	0	0	0	1	0
Start experimental work(sew)	3	2	2	2	2	2	2
Risk analysis and control(rac)	1	0	0	0	0	0	0
Development fund management(dfm)	1	0	0	0	0	0	0
Coordinate production planning(cpp)	1	0	0	0	0	0	0
Preparation of flight test equipment(pfte)	1	1	1	1	1	1	1
Quality review and confirmation(qrc)	2	2	2	2	2	2	1
Determine safety assurance measures(dsam)	1	0	1	1	0	1	1
Software engineering management(sem)	1	0	0	1	0	1	0
Organizational design review(odr)	2	0	0	0	1	1	0
Conduct range exercises(cre)	3	2	2	2	2	1	1
Conduct flight tests(cft)	3	3	2	2	3	2	2
Evaluation of technical index(eti)	2	2	2	2	2	2	0
Final documentation and review(fdr)	1	0	0	0	0	0	0
Status appraisal work(saw)	1	0	0	0	0	1	0
Small batch trial production(sbtp)	2	1	1	1	2	1	2

Fig. 4. Constructing an adjacency weighting matrix for the relationship between tasks and resources

5.3 Analysis of Key Nodes of the Equipment Development Project A

1) Analysis of key project task nodes: According to the project task adjacency matrix and the completion time of each project task, construct the project task network plan diagram. Fig. 5 and Fig. 6 shows the project task network plan diagram for the development of equipment development project A.

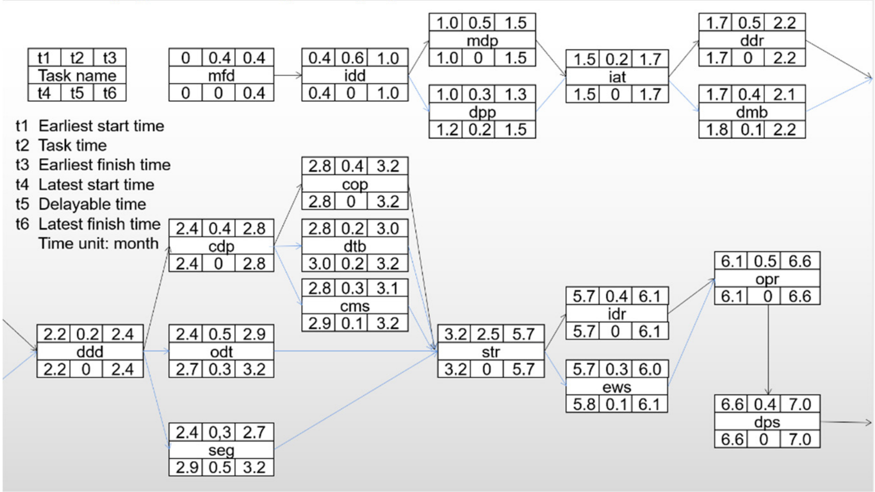


Fig. 5. Project task network plan diagram (1)

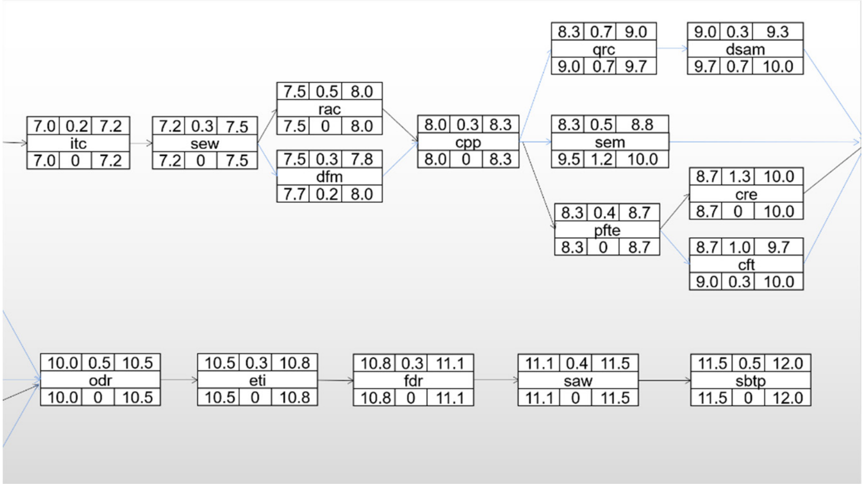


Fig. 6. Project task network plan diagram (2)

Based on the traditional CPM method to determine the critical path of the project task network plan diagram, the black arrow is labeled as the critical path. First of all, the project task nodes on the critical path are analyzed, and it can be seen from Figure 6 that the three network indicators of in-degree, out-degree, and betweenness are higher than the project tasks on the critical path, such as ddd, str, cpp, and odr. Any abnormality in any of these critical nodes will affect multiple project tasks and even the entire project schedule. Next, the project task nodes on the non-critical path are analyzed, and three project tasks, ews, dfm, and sem, are filtered according to the value of the network metrics. Setting the interference value $\Delta t = 0.5$, the project completion time increase values of the above three project task nodes respectively ΔT are 0.4, 0.3 and 0. Therefore, it can be judged that the project tasks ews as well as dfm are more critical, while sem is insensitive to the interference value and belongs to the non-critical node.

2) Analysis of key project organizational nodes: Firstly, according to the relationship matrix between project organizations and project tasks E_{potn} , the task participation network of project organizations is constructed. The nodes in the network represent the project organizations, and the connecting edges between the nodes indicate that two project organizations are involved in a project task at the same time. By analyzing the values of the network indicators for these nodes, the project organization nodes are classified into three categories. The first kind of nodes such as the planning management department, the project office, etc., have relatively high values, indicating their important role in the equipment development project network. The second kind of nodes such as technology department, finance department, etc., have values at a moderate level, indicating their importance is lower than the nodes in the first category. The last type of nodes such as graphic printing office, liaison department, etc., belong to the ”peripheral nodes” of the project organization, with significantly lower importance compared to the first two categories of organization nodes. Furthermore, it is necessary to conduct a comprehensive importance analysis throughout the entire project cycle for

the five most critical organizations in the first category. Based on the previous analysis of the structure of the equipment development project A, there are four relationships between the organization and the task: supporting, leading and approving. The weights of the relationships are specified as

$$AO_{ij} = \left\{ \begin{array}{ll} 1, & assisting \\ 2, & leading \\ 3 & approving \\ 0, & \text{h}ave\ not\ participated \end{array} \right\}$$

According to the formula for the importance of project organization nodes, calculate the node importance of the five project organization nodes at each moment in the full cycle of the equipment development project A. The momentary importance of these nodes plotted on a January cycle is shown in Figure 7.

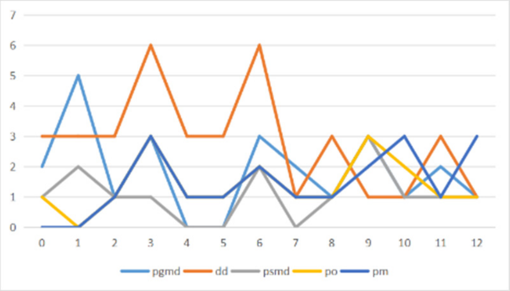


Fig. 7. Project organization node importance

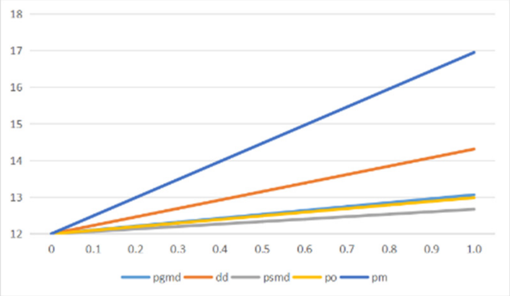


Fig. 8. Total time to completion for different probabilities of paralysis of the project organization

In order to further analyze the key organization nodes throughout the entire process, this paper adopts the method of assuming that the organizational nodes are paralyzed to analyze these five organizational nodes. Given the organizational paralysis penalty factor for a project task $\omega_1, \omega_2, \ldots, \omega_n = 1$, due to the existence of hierarchical affiliation between organizations in the equipment development project A, consider that when a project organization has a probability of being paralyzed p_{o_i}, its subordinate project organizations also have the same probability of being paralyzed. Calculate the completion time of each project task under the paralysis of project organization nodes according to the formula respectively. And then calculate the total project completion time under the organization paralysis, Figure 8 shows the total project completion time under different paralysis probability of each organization. As can be seen from the table, pm and dd are the most critical organizational nodes in the whole project, and their paralysis will greatly affect the completion of the project. Therefore, the project manager (pm) as well as the overall design department (dd) are the key organizational nodes of the A-equipment development project.

3) Nodal analysis of key project resources: Based on the previous analysis of the structure of the equipment development project A, there are four types of relationships between tasks and resources: no need, small need, normal need and large need. The weights of the three relationships are specified as

$$AR_{ij} = \left\{ \begin{array}{ll} 1, & slight \\ 2, & medium \\ 3 & quantity \\ 0, & \text{h}ave\ not\ participated \end{array} \right\}$$

According to the project organization resource node importance formula, calculate the node importance of each moment of the seven project resource nodes in the full cycle of the equipment development project A, and plot the moment importance of these nodes in a cycle of one month as shown in Figure 9. Same as the analysis of key nodes of project organization, we adopt the method of assuming the scarcity of resource nodes to analyze these seven resource nodes. Set the resource scarcity penalty factor for the project task $\sigma_1, \sigma_2, \ldots, \sigma_{35} = 1$, and since there is a substitutable relationship between the resources in the A equipment development project, specify that if there are other resources that can be substituted for the project resource r_j in the project task a_i , then the resource scarcity has no impact on the completion time of the task. The completion time of each project task under the scarcity of each project resource is calculated separately according to the formula. In turn, the total project completion time under resource scarcity is calculated, and Figure 10 shows the total project completion time under different scarcity probabilities for each resource. From the figure, it can be seen that manpower and technology resources are the most critical resource nodes in the whole equipment development project A, and their scarcity will greatly affect the completion of the project. Therefore, manpower and technology resources are the key resource nodes of the equipment development project A.

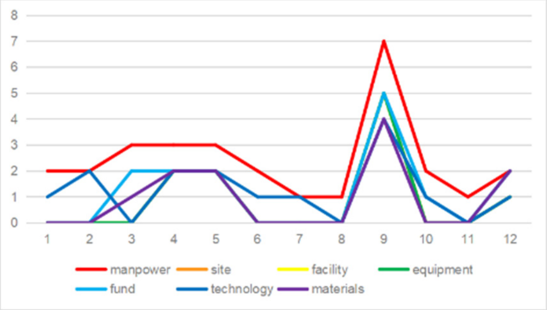


Fig. 9. Project resource node importance

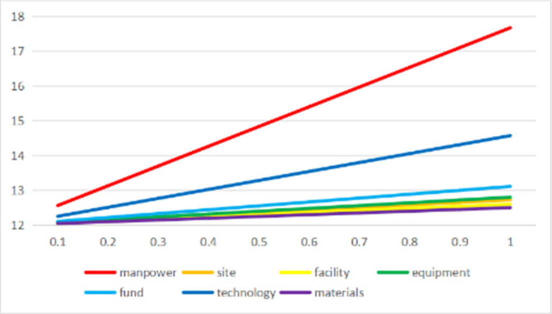


Fig. 10. Total time to completion with different probabilities of paralysis of project resources

6 Conclusions

This article proposes a hyper-network model for equipment development projects, as well as a method for identifying key tasks, organizations, and resource nodes. It overcomes the shortcomings of traditional analysis methods that separate organizations, tasks, and resources. Additionally, it presents an analysis method that considers organizational paralysis and resource scarcity. However, there are still areas for improvement in this research. For example, the calculation of penalty coefficients could be derived from more scientific methods, and there is potential to consider other complex relationships among project tasks. These shortcomings are worth exploring and further researching.

References

1. SCHIMMELPFENNIG, JÖRG.F-35 O-Ring Production Functions versus Mosaic Warfare: Some Simple Mathematics.[J].Air & Space Power Journal,2021,Vol.35(3): 76-83
2. Yabo Zheng, Lixia Wang, Xiaoming Dong, Linzhou Xu. The Architecture Design of A UUV Swarm System Based on Distributed Operation Theory[A]. The 19th International Symposium on Distributed Computing and its Applications [C],2020-10-16
3. Qing Yang; Yingxin Bi; Qinru Wang; Tao Yao. Batch-based agile program management approach for coordinating IT multi-project concurrent development[J].Concurrent Engineering,2021,Vol.29(4): 343-355
4. Amira Sharon; Olivier L. de Weck; Dov Dori. Improving Project–Product Lifecycle Management with Model–Based Design Structure Matrix: A joint project management and systems engineering approach[J].Systems Engineering,2013,Vol.16(4): 413-426
5. Shujun Yang; Gen Wang; Jirong Ma; Jianqiang Zheng & Duansong Li. Application of Big Data on Antiaircraft Weapon Equipment Research and Development[A].Proceedings of 2022 Chinese Intelligent Systems Conference[C],2022
6. J. Baschin;T. Huth;T. Vietor. An Approach for Systematic Planning of Project Management Methods and Project Processes in Product Development[A].2020 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM)[C],2020

7. Mohmmad Anvar Adibhesami; Ahmad Ekhlassi; Ali Mohammad Mosadeghrad; Amirhossein Mohebifar. Improving Time-Cost Balance in Critical Path Method (CPM) Using Dragonfly Algorithm (DA)[J].International Journal of Industrial Engineering and Production Research,2019,Vol.30: 187-194
8. Siripurapu, Adilakshmi; Nowpada, Ravi Shankar; Rao, K. Srinivasa. Improving Dijkstra's algorithm for Estimating Project Characteristics and Critical Path.[J].Reliability: Theory & Applications,2022,Vol.17(4): 65-73