Method for delaying responsibility allocation of power grid infrastructure projects considering logical relationship between engineering processes

ZHANG Jian¹, JIN Xianing², YANG Weihong³, AI Fangxin³, LI Zhanjun⁴, LI Menglu⁵, DE Gejirifu⁵

¹ State Grid Corporation of China CO., LTD., Beijing, 100031, China.
² State Grid Economic and Technological Research Institute CO., LTD., Beijing, 102209, China.
³ State Grid Liaoning Electric Power CO., LTD., Shenyang, 110004, China.
⁴ State Grid Liaoning Economic and Technological Research Institute CO., LTD., Shenyang, 110000, China.
⁵ School of Economics and Management, North China Electric Power University, Beijing 102206, China.

the corresponding e-mail: dove@ncepu.edu.cn

Abstract. Delaying responsibility allocation is one of the important contents in the construction management of power grid infrastructure projects. Due to the large investment in power grid infrastructure projects, long construction period and complicated operation procedures, many delays occurred during the construction process. Based on this, combined with the theory of time difference theory, this paper proposes a delay analysis method that considers the logical relationship between engineering processes. Secondly, the route time difference theorem is proposed, and the calculation steps and rules of the delay analysis method considering the logical relationship between engineering processes are given. Finally, the substation main structure construction project is selected as an example analysis, and compared with other methods, which effectively proved that the validity and feasibility of the proposed delay analysis method. The method of delay responsibility allocation proposed in this paper also provides ideas and directions for the subsequent research on delay assignment of similar construction projects.

1. Introduction

With the strategic goal of “three-type, two-network, world-class” proposed by the State Grid, it is particularly important to ensure the quality of the power grid infrastructure projects[1]. According to the data released by the China Electricity Council, the investment in the national grid infrastructure project in 2018 was 537.3 billion yuan, a year-on-year increase of 0.6%, which will bring greater social and economic benefits[2]. However, the power grid infrastructure project itself has a large scale of investment, a large number of participants, and a long construction period. It directly or indirectly causes the project to be completed on time, resulting in delays in the project and over budget[3]. Based on this, the logical relationship between the various engineering processes in the implementation...
process of the grid infrastructure project is analyzed, and the reasonable allocation of the delay responsibility of all parties in the construction project is the focus of research.

After the existing literature, many scholars have carried out a lot of research on the distribution of responsibility for power grid infrastructure projects. According to the delay of responsibility, the responsibility of the owner, contractor or third party is divided into forgivable delays and unforgivable delays. For example, Wang XIAOqi[4] et.al have used engineering justice to identify the responsibility for delays in construction project construction. Zhao Dongmei[5] et.al used structural equation modeling to analyze the project delay liability problem. Wang Renchao[6] et.al used the original plan network plan to compare with the actual implementation of the network plan, and proposed the construction project delay responsibility sharing model. Sun Chunling[7] et.al studied the mechanism of the impact of customer source delay on the income of PPP projects, and proposed preventive measures. At the same time, the above research also considered the delay in the construction project. For example, Liu Min[8] et.al use the Shapley method to quantitatively share delay liability, and construct a model of multi-agent common delay conditions, effectively solving the problems of delays in construction delays and other delays. Hong Ke[9] et.al used dynamic network analysis to analyze issues such as delays in construction period.

In terms of the responsibility allocation method for power grid infrastructure projects, the net impact method, the plan and actual period comparison method, the time impact analysis method, the plan impact analysis method and the overall impact method are mainly adopted. Scholars such as Rodica[10] have proposed using the Shapley-Shubik method to determine the delay liability of both parties to the construction project. In order to solve the concurrency delay in the construction project, Youngiae Kim[11] et.al proposed the concept of delay section, and divided the delay section into a single delay and multiple delay sections for analysis. Ishwar Adhikari[12] et.al used the analytic hierarchy process to construct a construction project delay analysis model. Scholars such as Kumaraswamy[13] conducted a survey of engineering projects in Hong Kong, and analyzed the available net impact method and the comparison between the planned and actual construction period methods. Scholars such as David[14] have found that the time impact analysis method has the highest recognition degree and the plan impact analysis method has the lowest degree of recognition when the same project delays responsibility distribution. Nuhu[15] et.al conducted a questionnaire survey on various types of construction projects in the UK, and obtained three kinds of delay analysis methods, such as plan and actual comparison method, influence method and net impact method. Anania[16] et.al analyzed the individual impacts and common influences of each event on the construction project duration by finding the intersection of various delay events, so as to allocate the delay responsibility for each process. Although the method has the advantages of being intuitive and easy to understand, when there are multiple concurrent delays in the construction project, the calculation amount is too large, which is likely to cause distortion and cause unreasonable distribution of delay responsibility.

To sum up, the existing power grid infrastructure project delays the responsibility allocation method. Although the problem of time difference ownership is considered, the delay liability is based on the principle of “who uses first, who owns” or “equal distribution”. Considering no logical relationship or impact between engineering processes, resulting in a lack of rationality in the allocation of delays in construction projects. Based on this, this paper applied the route time difference theorem. By considering the influence and logical relationship between the various processes in the grid infrastructure project, a more reasonable method of delay responsibility distribution is proposed, which is more widely used. The comparison with the higher recognition method is carried out to further verify the scientificity and effectiveness of the proposed method.

2. Basic theory

In the 1960s, DuPont proposed the key route method for construction projects and the time parameters[17-18] for each process. Subsequently, Yan Jianxun et al[19] scholars conducted in-depth research on the time difference characteristics of CPM networks. In the actual power grid infrastructure project delay allocation method, the responsible parties of the parties suffer large losses,
such as property loss, income reduction or interest increase; contractors increase labor costs, reduce productivity and increase mechanical parking costs. And other losses. Therefore, with the characteristics of time parameters in the time difference theory, it is of great significance to analyze the responsibility of delays in power grid infrastructure projects. The time parameter description of each process is as follows:

1. Earliest start time
   In the implementation process of the grid infrastructure project, the time from the left to the right to wait for all the pre-processes to complete can be called the earliest start time for the process \((i, j)\), ie \(ES_y\). The mathematical expression is:
   \[
   ES_y = \max \{ ES_{w} + T_{w} \} \quad \text{(1)}
   \]

2. The earliest end time
   In the implementation process of the grid infrastructure project, the corresponding duration is the earliest end time for the process \((i, j)\), ie \(EF_y\). The mathematical expression is:
   \[
   EF_y = ES_y + T_y \quad \text{(2)}
   \]

3. The latest start time
   In the implementation process of the grid infrastructure project, under the condition that the whole project is completed on schedule, according to the right-to-left principle, the latest start time of the arrow node is subtracted from the process duration, ie \(LS_y\). The mathematical expression is:
   \[
   LS_y = LF_y - T_y \quad \text{(3)}
   \]

4. The latest end time
   In the implementation process of the grid infrastructure project, The latest start time is the earliest start time of the process \(LS_y\) and the duration of the process \((i, j)\), ie \(LF_y\). The mathematical expression is:
   \[
   LF_y = LS_y + T_y \quad \text{(4)}
   \]

5. Total time difference
   In the implementation process of the grid infrastructure project, without affecting the total construction period of the construction, the total time difference is the maximum available maneuver time during the project \((i, j)\), ie \(TF_y\). The mathematical expression is:
   \[
   TF_y = LT_y - ET_y - d_y = LS_y - ES_y = LF_y - EF_y \quad \text{(5)}
   \]

6. Free time difference
   In the implementation process of the grid infrastructure project, without affecting the constraint of the earliest start time of the process after the construction project, the free time difference is the maximum maneuver time available during process \((i, j)\), ie \(FF_y\). The mathematical expression is:
   \[
   FF_y = ET_y - ET_{i} - d_y = ES_{y} - EF_y \quad \text{(6)}
   \]

3. Method of power grid infrastructure project delay considering the relationship between engineering processes

3.1 Route time difference theorem

**Theorem:** Regardless of the type of construction project’s CPM network, the sum of the free time differences of any route is equal to the time difference of the line, namely:

\[
TF_{\mu(i,j)} = \sum_{(i,j)\in \mu} FF_{(i,j)} \quad (7)
\]

**Proof:** Let \((j) = (w)\), \[\mu_{(s,i,j)} = ES_i - \sum_{(i,j)\in \mu} FF_{(i,j)} \], then
\[ |\mu(i,w)| = ES_w - \sum_{(i,w)\in \mu} FF_{\mu(i,w)} \] (8)

From the above formula (8),
\[ \sum_{(i,w)\in \mu} FF_{\mu(i,w)} = ES_w - |\mu(i,w)| \] (9)

At the same time, in the CPM network
\[ TF_{\mu(i,w)} = ES_w - |\mu(i,w)| \] (10)

Substituting the above formula (9) into (8),
\[ TF_{\mu(i,w)} = \sum_{(i,w)\in \mu} FF_{\mu(i,w)} \] (11)

which is
\[ TF_{\mu(i,j)} = \sum_{(i,j)\in \mu} FF_{\mu(i,j)} \] (12)

The certificate is completed.

3.2 Delayed responsibility allocation method

According to the route time difference theorem, by considering the free time difference of each process in the grid infrastructure project, the delay responsibility distribution method is proposed as follows:

1. In the progress network diagram of the completion network, if the original critical path has not changed, at this time, when the process on the critical path is delayed, the corresponding project delay responsibility must be assumed.

2. In the progress network diagram of the completion network, if the critical path in the original completion network progress map changes, the process on the path is first determined, if the delay process belongs to the direct impact set \(V\), it must affect the subsequent processes and bear the corresponding delays. If the delay process is an indirect impact set \(U\), it can be discussed in two cases.

**Case 1:** If the Date of Delay is less than or equal to the critical value, it means that the delay process does not affect the subsequent process, and only consumes the free time difference of the process itself. When the total project duration is delayed, the process does not need to bear the corresponding delay responsibility, and the number of days delayed in the subsequent discussion is recorded as \(DD\).

**Case 2:** If the number of days of process delay is greater than the critical value, it indicates that the delay of the process will affect the start time of the subsequent process and consume the free time difference that it owns and the free time difference that may consume the subsequent process. Therefore, When the total construction period is delayed, the operation must bear the corresponding delay responsibility.

3.3 Specific calculation steps

Combined with the route time difference theorem and the delay responsibility assignment method, the specific calculation steps of the power grid infrastructure project delay responsibility allocation method are as follows:

1. Find all the routes and key routes of the network according to the network plan progress chart of the grid infrastructure construction project;

2. Forming a set by the process on the key route of the construction project network, ie \(\Phi\);

3. Calculate the total time difference of each remaining process in the plan network schedule \((TF)\) and the free time difference \((FF)\);

4. The free time difference (also known as the critical value) calculated in the remaining network progress chart can divide the process into two sets, ie.
\[ V = \{ \text{a set that directly affects the subsequent processes} \} \]  
\[ U = \{ \text{a set with no effect the collection of subsequent processes} \} \]

Among them, \( V \) is the directly influence set, \( U \) is the indirectly influence set.

Which indirectly affects all the processes contained in the set, with free time difference, when \( DD_{i,j} \leq FF_{i,j} \), the start time of the subsequent process is not affected, and the process does not need to bear the corresponding delay liability. And when \( DD_{i,j} > FF_{i,j} \), it will affect the start time of the subsequent process and must bear the corresponding delay responsibility. The process directly involved in the collection does not have a free time difference. Therefore, as long as the process is delayed, it will directly affect the start time of the subsequent process, and must bear the responsibility for delay.

In summary, the specific calculation process of the method of delay responsibility allocation proposed in this paper is shown in Figure 1.

![Flow chart of delay responsibility distribution](image)

Figure 1 Flow chart of delay responsibility distribution

4. case analysis

4.1 Description of the problem
In order to verify the effectiveness of the proposed method, this paper selects a substation main structure construction project to analyze the example. The construction project follows the construction principles of “first underground, rear ground”, “first main body, rear enclosing”, “first civil construction, post-equipment”[20], construction starts from the ground excavation, and then the foundation and main wall 1 and 2, roof, building surface, internal construction, cleaning, door frame, outer wall, inner wall and top construction, the logical relationship and duration between each process, as shown in Figure 2.

![Network plan progress chart of substation main structure construction project](image1)

Figure 2 Network plan progress chart of substation main structure construction project

It can be seen from Fig. 2 that the planned completion time of the main structure construction project of the substation is 51 weeks, and the key route of the project is 1-2-3-4-5-7-9-10. However, during the construction of the main structure of the substation, due to improper construction management, inadequate preparation of raw materials and strikes by construction personnel, some processes in the main structure construction project of the substation were delayed, as shown in Table 1.

| Process   | Delay days/week |
|-----------|-----------------|
| (1, 2)    | 3               |
| (1, 7)    | 6               |
| (1, 8)    | 4               |
| (4, 5)    | 3               |
| (4, 6)    | 4               |
| (7, 9)    | 2               |
| (8, 9)    | 4               |

Combined with the number of days of delays in each process of the substation main structure construction project given in Table 1, the actual completed network plan, as shown in Figure 3.

![Network completion progress chart of substation main structure construction project](image2)

Figure 3 Network completion progress chart of substation main structure construction project
It can be seen from Fig. 3 that the construction period of the main structural construction project of the substation is extended from 51 weeks to 59 weeks after the number of delays in the various processes. At the same time, the key route of the project changed from the original one, namely 1-2-3-4-5-7-9-10 to two, namely 1-2-3-4-5-7-9-10 and 1-2-3-4-6-8-9-10. Therefore, the number of days of delay responsibility for each process is discussed and analyzed in detail as follows.

4.2 Analysis of results

4.2.1 This paper proposes an analysis of the method of delay responsibility allocation

According to the method for assigning responsibility for delays in power grid infrastructure projects proposed in this paper, the first step is to calculate the total time difference ($TF$) of all operations except key operations based on the schedule network schedule and free time difference ($FF$), as shown in Table 2.

| Process | $FF$ | $TF$ |
|---------|------|------|
| (1,7)   | 1    | 7    |
| (1,8)   | 4    | 3    |
| (4,6)   | 0    | 2    |
| (6,8)   | 0    | 2    |
| (8,9)   | 3    | 2    |

The second step, combined with the calculation results of Table 3, identifies the remaining process subordinate collections, i.e.

$$U = \{(1,7), (1,8), (8,9)\}$$

$$V = \{(4,6), (6,8)\}$$

In the third step, combined with the impact of the set of influences, each delay process is added to analyze and discuss the delay responsibility distribution. The specific scenarios are as follows:

Scenario 1: After loading the delay process, only one key route 1-2-3-4-5-7-9-10 is considered, indicating that the original project critical route has not changed, and the process belonging to the critical route is delayed. This Scenario will inevitably bear the delay responsibility, as shown in Table 3.

| Process | Bear the number of days (weeks) |
|---------|--------------------------------|
| (1,2)   | 3                              |
| (4,5)   | 3                              |
| (7,9)   | 2                              |

Scenario 2, after loading the delay process, the key route of the original project has changed, that is, the key route becomes 1-2-3-4-6-8-9-10. Then, only considering the critical route after the occurrence of the delay responsibility distribution, it is necessary to calculate whether each process has an available free time difference. At the same time, process $(4,6)$ is the directly affecting process, the process $(8,9)$ is the indirectly affecting process, and $FF_{(8,9)} = 3 < DD_{(8,9)} = 4$, we can get the delay responsibility of each process, which is shown in Table 4.

| Process | Bear the number of days / week |
|---------|-------------------------------|
| (1,2)   | 3                             |
| (4,6)   | 4                             |
| (8,9)   | 1                             |
Scenario 3, after loading the delay process, the original project key route becomes two, namely 1-2-3-4-5-7-9-10 and 1-2-3-4-6-8-9-10. When considering the above two key routes, the delay liability long list is analyzed as follows.

(1) (1,2) is the directly affecting process, and the delay of the process will inevitably lead to delays in the total project duration. At the same time, (1,2) is a single delay and should be responsible for three weeks of delay.

(2) When process (4,5), (4,6) and (7,9), (8,9) delaying the distribution of responsibilities, it is necessary to consider whether there is a delay in the occurrence of the delay, that is, the process (4,5), (4,6) need bear three weeks of corresponding delay responsibility, each process has been shown in Figure 4.

![Figure 4 Process (4, 5) (4, 6) delays in each time period](image)

As can be seen from Figure 4, When there is a delay in the process (4,5), (4,6), there is a delay in the concurrent. Therefore, the process (4,5) takes 1 week of delay responsibility, the process (4,6) takes 2 weeks of delay responsibility.

Process (7,9), (8,9) take two weeks of delay responsibility, each process has been shown in Figure 5.

![Figure 5 Process (7, 9) (8, 9) delays in each time period](image)

As can be seen from Figure 5, When there is a delay in the process (7,9), (8,9), there is no delay in the concurrent. Simultaneously, (8,9) is an indirect process that has a free time difference. Therefore, further calculate difference between the amount of free time of (8,9) and the delay, ie $DF_{(8,9)} = 3 < DD_{(8,9)} = 4$. The results showed that the process (8,9) will also affect one week during the total project, at which time it will be treated according to concurrent delays. Therefore, the process (7,9) will take 1.5 weeks of delay responsibility, the process (8,9) will take 0.5 weeks of delay responsibility.

In summary, using the delay responsibility allocation method proposed in this paper, the delay responsibility of each process of the substation main structure construction project is as shown in Table 5.

| Process | Bear the number of days / week |
|---------|--------------------------------|
| (1,2)   | 3                              |
| (4,5)   | 1                              |
| (4,6)   | 2                              |
| (7,9)   | 1.5                            |
| (8,9)   | 0.5                            |

Table 5 Distribution of delay responsibility for each process
4.2.2 Comparison analysis with other delay responsibility allocation methods

The existing delay liability allocation method with high degree of recognition and wide application range is selected including the plan and actual time comparison method and time impact analysis method. The results are shown in Table 6.

| Process method                     | (1,2) | (1,8) | (4,5) | (4,6) | (7,9) | (8,9) | (1,7) |
|------------------------------------|-------|-------|-------|-------|-------|-------|-------|
| Comparison of schedule and actual  | 3     | 0     | 3     | 4     | 2     | 4     | 0     |
| schedule                           |       |       |       |       |       |       |       |
| Time impact analysis               | 3     | 0     | 3     | 1     | 2     | 1     | 0     |
| Delayed responsibility allocation  | 3     | 0     | 1     | 2     | 1.5   | 0.5   | 0     |
| method proposed in this paper      |       |       |       |       |       |       |       |

It can be seen from Table 6 that for the same substation main structure project, different delay responsibility allocation methods are used to delay the distribution of responsibility. The details are as follows:

1. The comparison between the schedule and the actual schedule plan only needs to compare the construction project network plan map and the completion plan map to delay the distribution of responsibility, and does not consider the complicated situation such as the key route change of the construction project and its concurrent delay, resulting in the responsibility of each process. The number of days of delay is greater than the number of days of actual delay.

2. The construction project schedule is cut into multiple panes by time impact analysis method, and various delay events are loaded, but the occurrence of concurrent delays is directly ignored, resulting in the total delay days of the project will be greater than the actual delay days.

3. The method of allocation of delay responsibility proposed in this paper not only considers the delay of construction projects, but also considers the free time difference and total time difference of each process in the construction project. The assigned delay and responsibility results are more reasonable and reliable.

5. Conclusion

This paper introduces the concept of maneuver time in the time difference theory into the delay responsibility distribution of power grid infrastructure projects, and obtains good results, and has certain reference value. The specific conclusions are as follows:

1. The method of assigning responsibility for delays, which takes into account the logical relationship between processes, breaks the principle of “first come, first served” of maneuver time, and scientifically considers the logical relationship between processes, which is more reasonable.

2. This paper proposes that the delay responsibility allocation method is more reasonable than the existing delay responsibility distribution method.

In summary, the method of delay responsibility allocation for power grid infrastructure projects proposed in this paper has more promotion value and significance. However, it is necessary to support computer technology. Otherwise, for large-scale construction projects, the amount of calculation is too large and the resources are wasted, which is also a key direction for future research.

Acknowledgments

This research was financially supported by science and technology project of State Grid Corporation of China (SGCC) “Research on multi-target sequence prediction model and dynamic warning for power grid infrastructure projects” (Grant No. B3441318K001).
References

[1] Fu Zhixin, Li Yiyi, Yuan Yue. Discussion on the key technologies of ubiquitous power internet of things [j]. Power Construction. 2019(5), 1-5.

[2] China Electricity Council. China Power Industry Annual Development Report 2018. http://www.cec.org.cn/yaowenkuaidi/2018-06-14/181765.html.

[3] Wang Liufei, Xie Zhenan, Wang Xiangqian, Li Huizong. Research on risk factor model of construction project delay [j]. Journal of Handan University. 2016(2). 86-90.

[4] Wang Xiaojun. Discussion on the identification of delays in the construction of judicial appraisal project construction project [j]. Global Market Information Herald. 2017(2): 102-103.

[5] Zhao Dongmei, Wang Xiaojun, Hou Lina. Research on Key Risks of Construction Project Delays [j]. Technology Economics and Management Research. 2009(5): 48-50.

[6] Wang Renchao., Qi Chunhao, Ouyang Bin. Research on Engineering Delay Liability [j]. Journal of Hydroelectric Engineering. 2004(2). 6-11.

[7] Sun Chunling, Ji Yu. The mechanism and prevention of the forgiveness of the construction period delay on the income of the ppp project [j]. Value Engineering. 2018(8): 33-38.

[8] Liu Min, Mao Yuchen. Research on Common Delay Responsibility Sharing Based on Improved Shapley Value [J]. People's Pearl River. 2018(4): 89-93.

[9] Ke Hong, Wang Jinzhao, Chen Qu. Research on Delayed Claim Method for Multi-event Construction Period [J]. Journal of Engineering Management, 2015.29(3): 35-39.

[10] Rodica Branzei, Giulio Ferrari, Vito Fragnelli, Stef Tijs. Two Approaches to the Problem of Sharing Delay Costs in Joint Projects [J]. Annals of Operations Research 109, 2002(08):359-374.

[11] Youngjae Kim, Kyungrai Kim, and Dongwoo Shin. Delay analysis method using delay section [J]. Journal of Construction Engineering and Management, 2005, 131(11): 1155-1164.

[12] Issaka Ndekugri, Nuhu Braimah, Rod Gameson. Delay Analysis within Construction Contracting Organizations [J]. Journal of Construction Engineering and Management, 2008, 134(9): 692-700.

[13] M.M.Kumaraswamy, K. Yogeswaran. Substantiation and assessment of claims for extensions of time [J]. International Journal of Project Management, 2003 , 21:27-38.

[14] David Arditi, Thanat Pattanakitchamroon. Analysis methods in time-based claims [J]. Journal of Construction Engineering and Management, 2008, 134(4): 242-252.

[15] Issaka Ndekugri, Nuhu Braimah, Rod Gameson. Delay Analysis within Construction Contracting Organizations [J]. Journal of Construction Engineering and Management, 2008, 134(9): 692-700.

[16] Anania Mbabaz, Tarek Hegazy, Frank Saccomanno. Modified but-for method for delay analysis [J]. Journal of construction engineering and management, 2005, 131(10): 1142-1144.

[17] Zhang Lihui, Zu Xin, Huang Yuansheng, Qi Jianxun. Time difference analysis of repetitive project scheduling model [j]. China Management Science. 2018(6), 95-101.

[18] Li Xingmei, Zhang Qian, Wei Hanjing. Research on maneuver time based on hierarchical network [j]. China Management Science. 2015(6), 147-152.

[19] Zhai Jianxun, Zhang Lihui, Li Xingmei. Theory of maneuvering time characteristics in network plan management and its application [d]. Science Press, 2009.

[20] He Qinghua, Liu Xiaoxue, Wang Ge, Yan Dafei, Wan Jingyuan. Research on Knowledge Communication in Organizational Evolution of High-tech Zone Construction Projects from the Perspective of Meta-network [J]. Journal of Engineering Management, 2019(4), 107-112.