Analysis Of Concurrent Delays on Multiple Critical Paths

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(Received 31 / 1 / 2021. Accepted 30 / 1 / 2022)

□ ABSTRACT □

Delay analysis is an important problem in construction management. The analysis is difficult when there are concurrent delays. Sorting concurrent delays is a basic step during analysis. A suitable technique must be used to apportion compensation or damages in an equitable manner.

In this research, the problem of concurrent delays is discussed in detail and the difference between concurrent delays on delayed critical paths and primary critical paths is also discussed. Consequently, concurrent delays are considered on primary critical paths only.

Many problems related to multiple primary critical paths with or without concurrent delays are introduced in this research. The author proposes a new method called the percentage method, which overcomes the presented problems. The new method can be used in the following cases: one primary critical path or multiple primary critical paths with or without concurrent delays.

Keywords: Construction Management, concurrent delays, Delay analysis

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تحليل التأخيرات المتزامنة على مسارات حرجة متعددة

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(تاريخ الإيداع 31 / 1 / 2021. قُبِل للنشر في 30/ 1 / 2022)

□ ملخّص □

تحليل التأخيرات هو مشكلة هامة في إدارة التشييد، و يكون التحليل صعبًا عند وجود تأخيرات متزامنة. لذلك يعد تصنيف التأخيرات المتزامنة خطوة أساسية أثناء عملية التحليل. يجب استخدام تقنية مناسبة لتوزيع التعويضات أو الأضرار بطريقة عادلة بين الأطراف.

تم في هذا البحث مناقشة مشكلة التأخيرات المتزامنة بالتفصيل ، كما نوقش الفرق بين التأخيرات المتزامنة على المسارات الحرجة المتأخرة والمسارات الحرجة الأولية. وبالتالي ونتيجة المناقشة تبين أن التأخيرات المتزامنة هي التأخيرات على المسارات الحرجة الأولية فقط.

تم طرح العديد من المشكلات المتعلقة بالمسارات الحرجة الأولية مع أو بدون تأخيرات متزامنة في هذا البحث. في النهاية تم اقتراح طريقة جديدة تسمى طريقة النسبة المئوية ، والتي تتغلب على المشاكل المطروحة في البحث حيث يمكن استخدام الطريقة الجديدة في الحالات التالية: مسار حرج أولي واحد أو عدة مسارات حرجة أولية مع أو بدون تأخيرات متزامنة.

الكلمات المفتاحية: إدارة التشييد ، التأخيرات المتزامنة، تحليل تأخيرات

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Introduction:

Concurrent delays are defined as two or more delays, which are totally independent and if considered individually would affect the project completion date according to CPM schedule (Rubin et al. 1983, Bartlett 2002). Concurrency is only significant where both delayed activities are critical to project completion (Karaiem and Diekmann 1987).
Concurrent delays are classified as follows (Eldosouky 1996):

1. Excusable delay and non-excusable delay.
2. Excusable delay and compensable delay.
3. Excusable delay, non-excusable delay, and compensable delay.
4. Non-excusable delay and compensable delay.

Concurrent delays with an excusable delay will generally be considered as excusable delays. For these delays the contractor is entitled to time extension if the delays are on the critical path. This protects him from any resulting liquidated damages. For concurrent non-excusable and compensable delays, the contractor is allowed a time extension for completion with each party suffering its own losses. The contract clauses should declare the method of evaluation of such claims (Eldosouky 1996).
For concurrent delays in which the owner and the contractor are both responsible for delays in completing the work, there are two different rules which were presented by Karaiem and Diekmann (1987). These rules are called the easy rule and fair rule. Table (1) summarizes concurrent delay remedies according to previous rules.

Table 1 Easy and Fair Rules

Concurrent delay	Remedy (For Critical Path)	
Any Delay Concurrent with Excusable	Time Extension	
Concurrent (Compensable / Non-Excusable)	Easy Rule	Fair Rule
	Time extension	Apportionment

Ness et al. (2000) classified concurrent delay according to the causes of delay, which has effect on one or two activities.

Concurrent Delays Analysis Techniques

Since time translates to money it is important to be able to determine the responsibility for the project's delays in a manner that is equitable to the owner and the contractor. This determination is straightforward when only one party is responsible for the delays, but it is difficult to assign when various parties create delays especially concurrent delays. There are many researches discussed the techniques used in analysis of concurrent delays. They are:
Karaiem and Diekmann (1987) developed a technique to analyze concurrent delays by making an adjustment to the as-built schedule to include different types of delays. The technique deals with concurrent delays when the critical activities are identical in both as-planned and adjusted as-built schedules. The adjustment consists of allocating a different code to critical, non-critical, and delay types. Therefore, a group of adjusted bar graphs is prepared. In these bar graphs the duration of each activity is replaced by a code. For example, X represents the normal non-critical activity; Y normal critical activity in critical path Y; Z normal critical activity in critical path Z, they should appear on a bar chart with symbols showing those delays. New symbols used in the as-built bar chart for the concurrent delays.

Bartholemew (1989) and Logcher (1989) discussed Kraiem and Diekmann work. They said that the as-planned schedule (as-planned critical paths) seldom constitutes the criterion for measuring actual fulfillment of the work as the authors claim. Contractors are seldom contractually bounded to as-planned schedule. The as-planned schedule can reasonably be taken as the starting point.
The main criticism of this technique is that it presents a method for concurrent delay analysis when the as-planned and as-built critical paths are identical, despite the fact that the critical paths may be changed during project execution.
Arditi and Robinson (1995) presented the various delay scenarios that may cause concurrent delay and different combination of delay types. The combination was presented for all types of delays (owner, contractor, neither) for two and three activities. A dynamic approach was proposed in determining concurrent delays scenarios. This approach considers that CPM network may change day by day, depending on delays and accelerations that occurred the day before. The researchers find that the day by day method is complex because the combination and criticality of every activity must be determined every day. This method is interested in apparent critical paths in each day to determine concurrent delay and this consideration may give inaccurate results.
Eldosouky (1996) modified Kraiem and Diekmann technique for analysis of concurrent delays. In this technique as-planned and as-built schedules are plotted in the same scale. The following legend is used to draw the as-built schedule: (o), (c), and (n) to represent compensable, non-excusable, and excusable delays respectively. The difference between as-built primary critical paths duration and as-planned project duration represents the total project delay. The primary paths (which the longest networking duration) are determined and concurrent delays are calculated for delays occurred at the same time on primary paths.
Jrad, Omran, and Zagbor (2007) studied the analytical and statistical results of a questionnaire regarding the reasons for delays of 333 local Syrian projects, of which 140 projects are in coastal zone, and 193 projects in Lattakia, Damascus, Aleppo, Tartaus, and Homs. Finally the study also presented a program for computation of the expected construction delay using AHP.
Ombir Rathee1, Chiterrekha Kabre (2018) discussed the current scenario in Indian construction industry about the delay analysis methods and Delay protocols used by the professionals. The research design was quantitative, where the data was collected from clients, consultants and contractors using questionnaires. The results obtained indicate that the top major causes of delay related disputes are due to lack of knowledge and use of Delay Analysis Methods and Delay related protocol in the country.
El Hakim, Yasmin (2020) highlighted how the Egyptian Law perceive concurrency; in addition to performing a comprehensive literature review for the accepted definitions for concurrent delays. The scope of this research includes how different countries law define concurrency and its remedy including Egyptian Law, English Law and the US Law.
Chintan Munvar; Desalegn Girma Mengistu, and Gangadhar Mahesh (2020) concluded that it is essential to recognize the nature and effects of concurrent delays that the Indian industry is facing. In this regard, cases in India were analyzed to understand the nature of concurrent delays, strategies adopted, and legal issues. Also, a survey of arbitrators and professionals with experience in delay disputes was conducted to (1) identify current approaches to concurrent delays in India and (2) determine the appropriateness of and challenges in applying approaches from the literature. In India, shortfalls exist in project

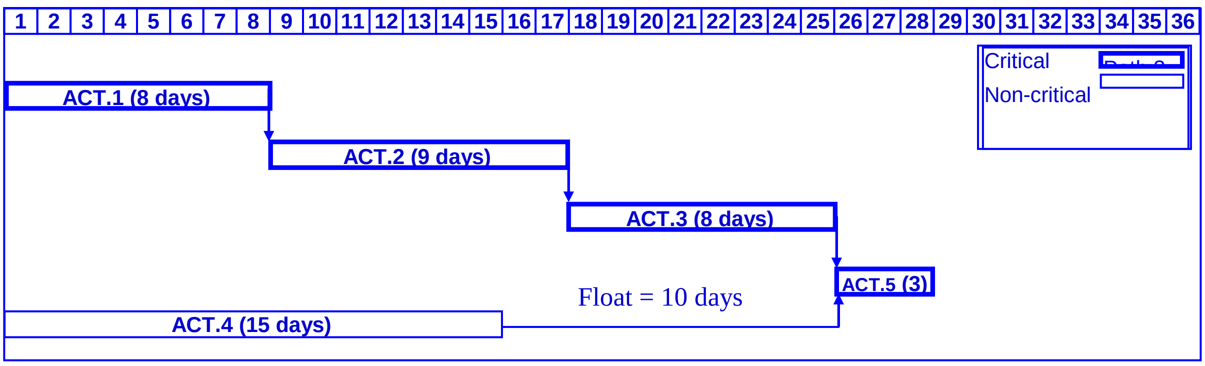
management processes and protocols. Also, documentation and information management systems are poor. These failings act as barriers to adopting advanced global practices.
Moneer Bhih,; and Tarek Hegazy, (2021) introduces an enhanced daily windows analysis (EDWDA) that combines the ability of the daily windows method to consider all critical path fluctuations, and the ability of the modified but-for method to analyze concurrent delays and accelerations. The EDWDA follows the day-by-day analysis of daily windows and, within each day, apportions multiday project consequence using the modified but-for method. To facilitate the application of EDWDA, a macro program was written on MS Project software and case studies were used to prove its ability to resolve the shortcomings of parent techniques.
Jarad Fayez,(2021) proposed method, which reflects the dynamic changes in the critical path(s) during the course of project.. Updating the as-planned schedule on an activity-by-activity (i.e. after the finish of changed activities) basis can realistically prove the dynamic nature of critical path. Delays and other changes are considered in the analysis and then the changes in critical path and project deadline is tested.

Research Importance and Objective:

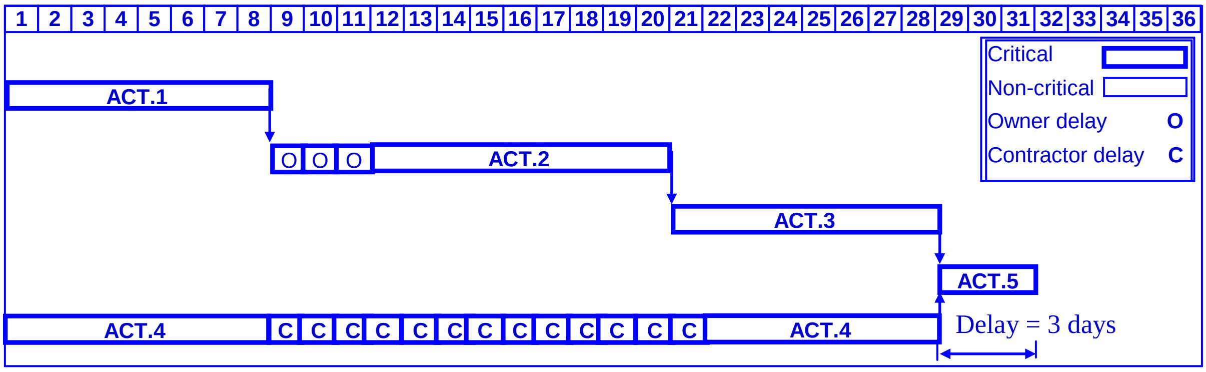
The existing techniques which analyze delays and work changes cannot be used for real-life projects. They are manual techniques. Most of them neglected the problem of work changes and concurrent delays. They give inaccurate results. The primary critical path is a path with longest networking duration of apparent critical paths (critical paths in the as-built schedule).
Therefore, a proposed model will be presented to analyze delays and work changes on multiple critical paths. This technique must give accurate result and can be used for real-life projects. Apportion the responsibility of parties towards total project delay. The apportionment method will not cause a dispute between the owner and the contractor.

Concurrent Delays and primary Critical paths

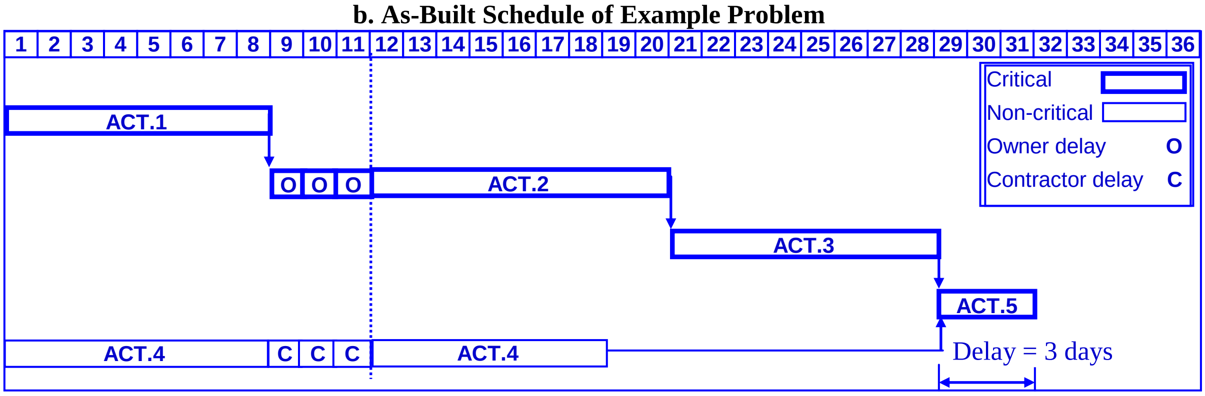
Consider the following scenarios regarding the example problem shown in Fig.1. The as-planned critical path runs through activities 1, 2, 3, and 5 and the corresponding project duration is 28 days as shown in Fig 1.a. Activity 4 has a float of 10 days. The as-built schedule is shown in Fig 1.b, in which activities 2 and 4 are delayed by 3 and 13 days, respectively. When considering this scenario, the owner may argue that the delays are concurrent because as-built schedule has two delayed critical paths and the delays occurred at the same time by the owner and the contractor at days 9, 10, and 11. At first glance this seems at least arguable. This is not true because it misinterpreted the critical path meaning.



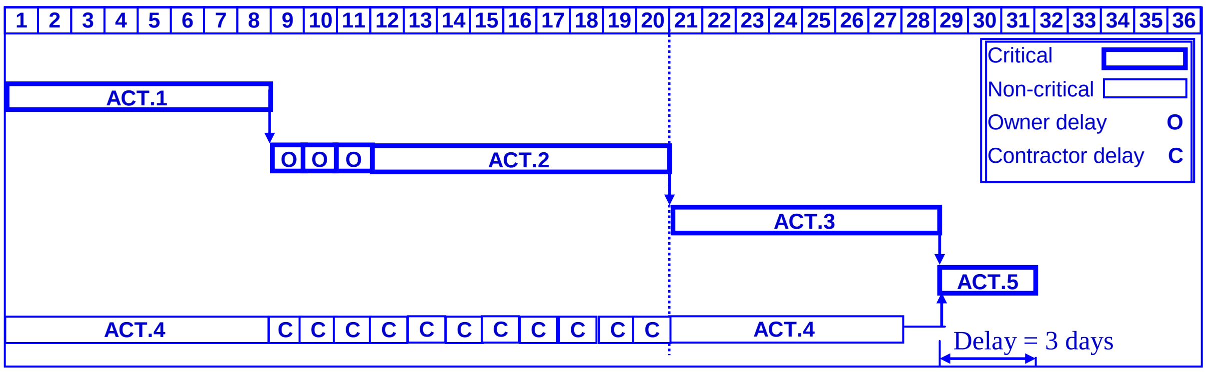
a. As-Planned Schedule of Example Problem



b. As-Built Schedule of Example Problem



c. As-Built Schedule of Example Problem after 11th Day

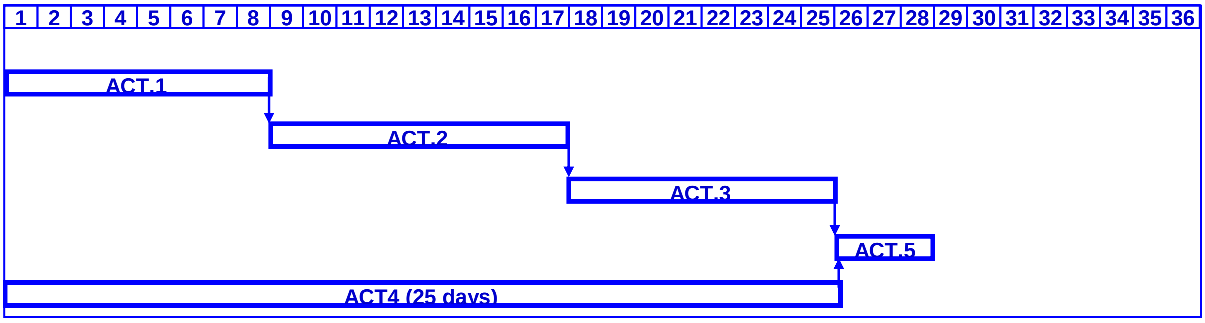


d. As-Built Schedule of Example Problem after the 20th Day

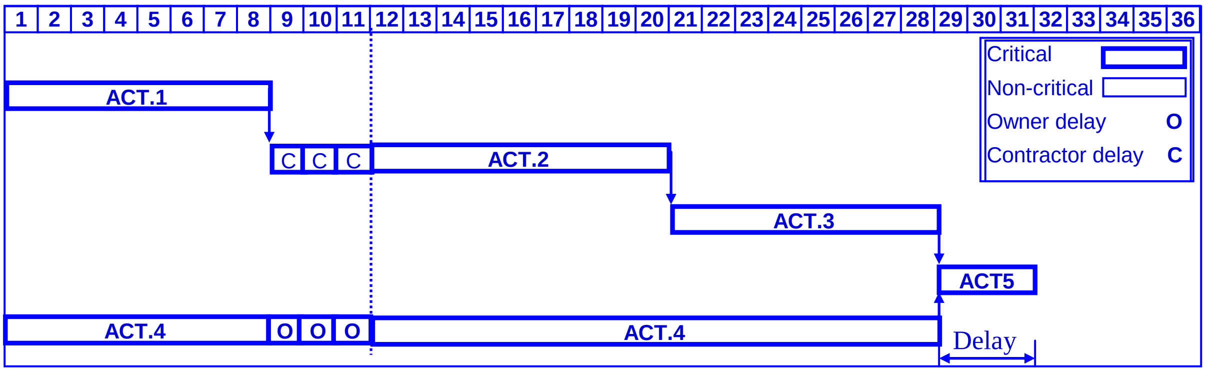
Fig.1 Concurrent Delays on Delayed Critical Paths under Different Scenarios

Referring to Fig.1.c, which illustrates the status of project after the 11th day. The delay of activity 2 still drives the project completion and thus activity 2 is ultimately critical, but activity 4 is not critical and does not affect project completion at this stage. Therefore, the concurrent delay of activity 4 does not impact the completion of the project. If as-built project status is recorded after the 20th day as shown in Fig.1.d, activity 2 is finished without any other delays and the delay of activity 4 is still going but still not impacting project completion, since activity 4 still has a float of 1 day. It is apparent that these delays are not concurrent in terms of criticality and the contractor should be awarded time extension and overheads against the delay in activity 2.

The true concurrency of the previous example can be seen when as-planned duration of activity 4 is 25 days as shown in Fig.2.a. In this case, actual concurrency is created when both activities 2 and 4 are delayed by 3 days as shown in Fig.2.b, in which the as-built schedule after the 11th day is presented and both activities 2 and 4 affecting project completion. In Fig.2.b, the two delayed critical paths have the same networking duration while in Fig.1 the delayed critical paths have not the same networking duration.
From previous discussion, concurrent delays are determined on primary critical paths only.



a. As-Planned Schedule (Activity 4 duration is 25 days)



b. As-Built Schedule

Fig.2 Concurrent Delays and Primary Critical Paths

Problems With Analysis of Delays on Multiple Critical Paths

Many problems may be encountered during analysis of delays on multiple critical paths with or without concurrent delays, they are:

1. Multiple primary critical paths have concurrent compensable delays

When compensable delays occur at the same time on two or more primary critical paths, will the owner pay overheads for his delays on one primary critical path or for his delays on all primary critical paths?. In Fig.3., compensable delays occur at the same time on two primary critical paths on the 5th day. The owner will pay two days overheads for his delays on the first primary critical path. Will the owner pay overheads for his delay on the 5th day of the second primary critical path?. If the owner pays overheads for his delay on the 5th day of the second primary critical path, overheads is paid twice by owner for the same day.

2. Multiple primary critical paths have concurrent non-excusable delays

Similar to the above case, will the contractor pay liquidated damages for his delays on one primary critical path or for his concurrent delays on primary critical paths?. Fig.4 shows that the 4th and 5th days are delayed by contractor on two primary critical paths. The contractor will pay three days liquidated damages for his delays on the first primary critical path. Will the contractor pay liquidated damages for the 4th and 5th days on the second primary critical path?. In this case, liquidated damages is paid twice by contractor for the same days.

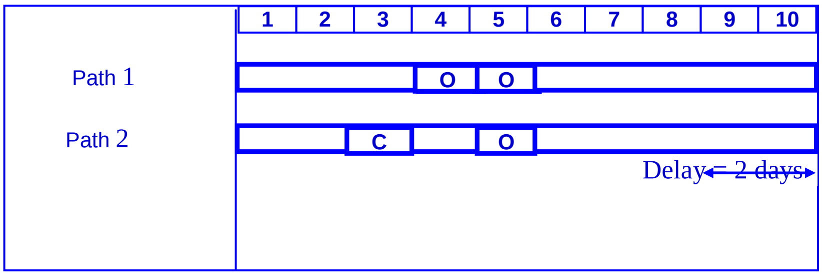


Fig. 3. Multiple Primary Critical Paths with Concurrent Compensable Delays

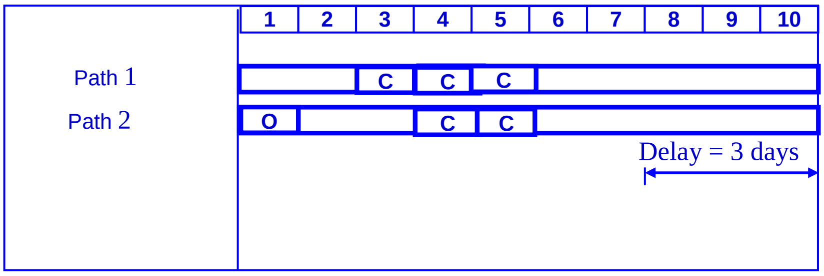


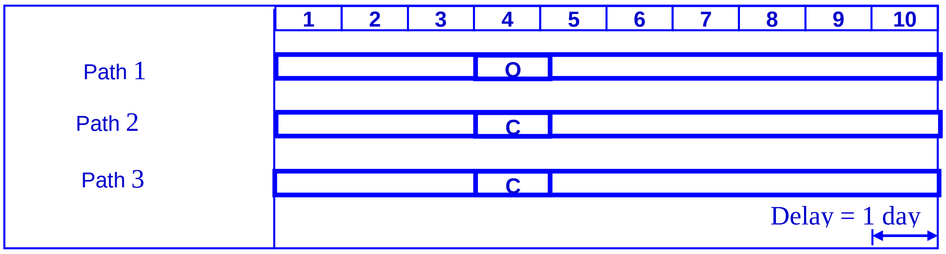
Fig. 4. Multiple Primary Critical Paths with Concurrent Non-excusable Delays

3. One primary critical path has a type of delays and another type of delays occurs concurrently on other primary critical paths.

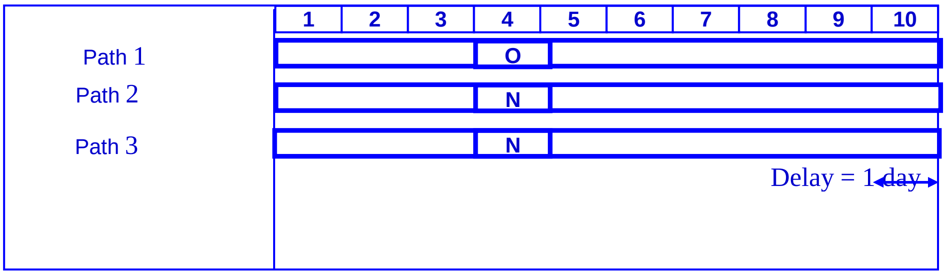
It is not exceptional to find, for instance, the first primary critical path has compensable delays and two other primary critical paths have concurrent non-excusable delays as shown in Fig.5.a. The question is which method can be used to assign the responsibility of delays?. Similarly, many arrangements of delays on multiple primary critical paths are shown in Figs.5. b, c, d, e, and f.

4. Two primary critical paths have concurrent delays and an other primary critical path does not have delays at the same time.

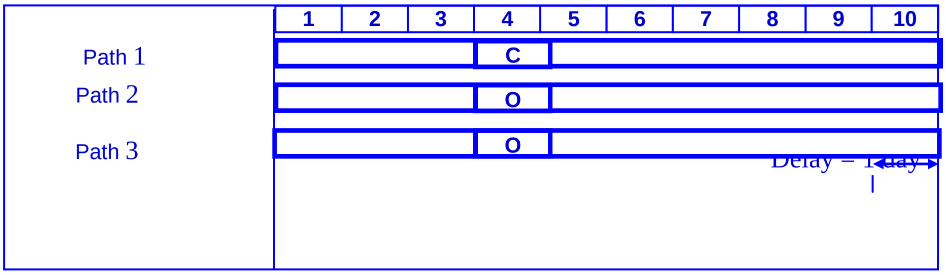
The analyst may find concurrent delays on two primary critical paths and no delays at the same time on a third primary critical path. For instance, there are concurrent compensable and non-excusable delays on the first and third primary critical paths while the second primary critical path does not have delays at the same time as shown in Fig.6.a. Another arrangements may be found for three primary critical paths two of them have concurrent delays and the other primary critical path does not have delays at the same time as shown in Figs.6.b, and c.



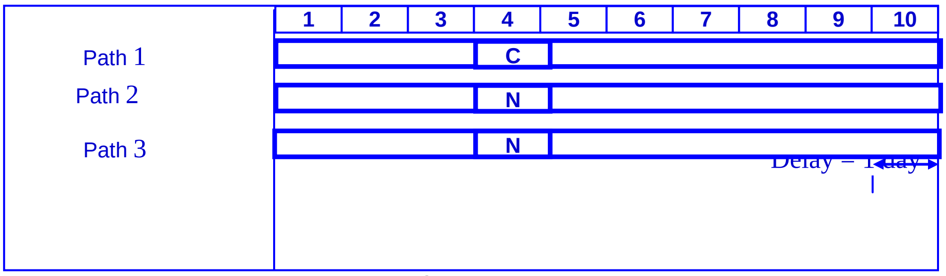
a. Concurrent compensable on the first path and non-excusable delays on the other paths



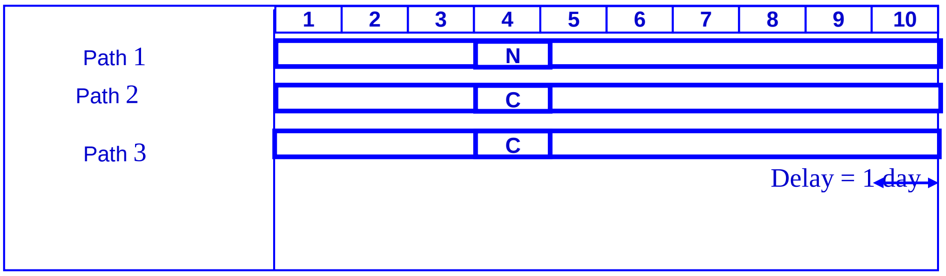
b. Concurrent compensable on the first path and excusable delays on the other paths



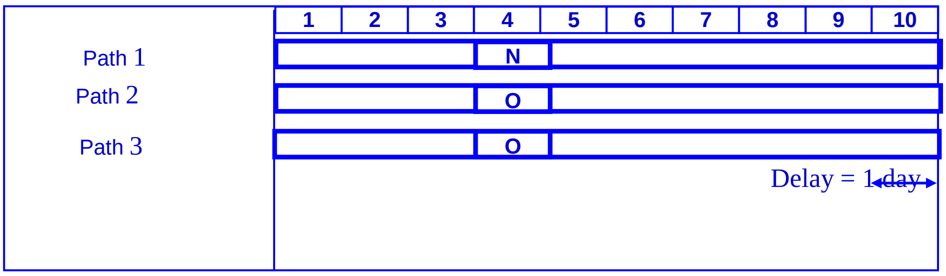
c. Concurrent non-excusable on the first path and compensable delays on the other paths



d. Concurrent non-excusable on the first path and excusable delays on the other paths

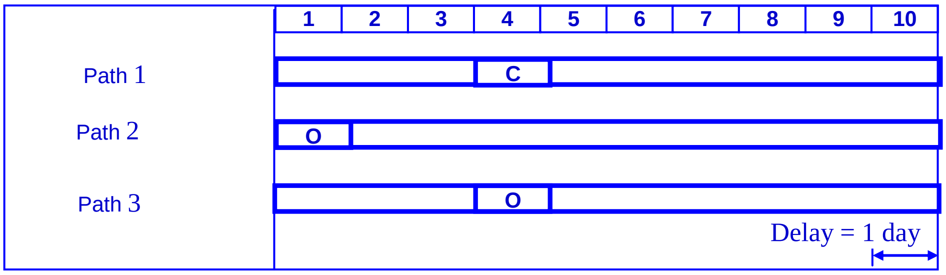


e. Concurrent excusable on the first path and non-excusable on the other paths

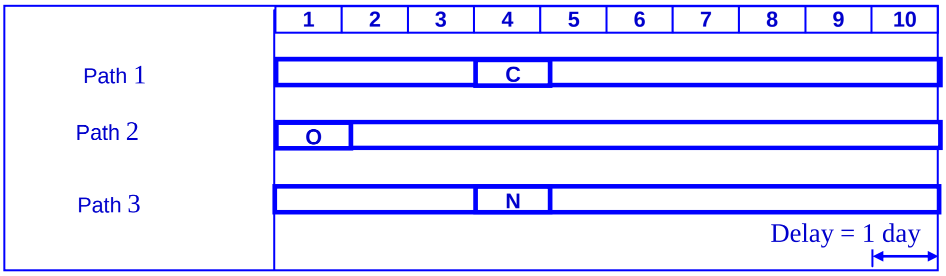


f. Concurrent excusable on the first path and non-excusable on the other paths

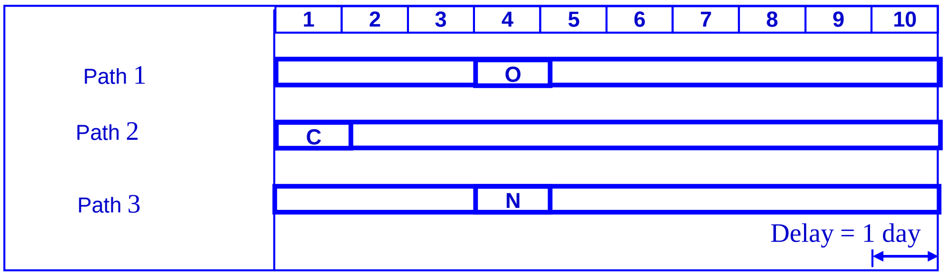
Fig.5 Problems of Concurrent Delays on Three Primary Critical Paths



a. Concurrent compensable and non-excusable delays on two primary critical paths only



b. Concurrent non-excusable with excusable delays on two primary critical paths only



c. Concurrent compensable with excusable delays on two primary critical paths only

Fig.6 Two Primary Critical Paths have Concurrent delays and No Delays at the Same Time on a Third Primary Critical Path

Generating The Path Matrix

A path may be viewed as a set of activities leading in succession from activity 1 to activity N. Some activities may be along more than one path. The network paths may be portrayed as a path matrix. The rows of path matrix represent all possible paths that commence at start activity and terminate at finish activity of the network, while its columns are sequence numbers of the activities lying on a specific path. Hence, the path matrix; P(j, i) is an PN×N matrix where:

$$P(j, i) = \begin{cases} 1 & \text{if activity } i \text{ belongs to path } j. \\ & \text{Otherwise.} \end{cases} \qquad \begin{matrix} i=1, 2, \dots, N \\ j=1, 2, \dots, PN \end{matrix}$$

Where, PN is number of paths of the network, and N is number of activities in the network. Network paths can be generated from last activity to first activity of a network based on activities predecessors. In addition, they can be generated from start activity to last activity based on activities successors. This is because, all network paths must start at first activity and terminate at last activity of the network. The path matrix of the network will be generated from first activity to last activity in the proposed method of this research.

The path matrix will be generated based on activities successors and their step numbers. The successors of an activity may belong to different step numbers as shown in Fig.7. It is noted that successors of activity 2 are activities 4, 5, and 8 which belong to step numbers 3, 3, and 4 respectively. Hence, the paths which branch from activities 4, 5, and 6 (that belong to step number 3) must be generated first, then the procedure generate the paths which branch from activities 7 and 8 (which belong to step number 4). Consequently, step numbers will be used for logical consideration of the activities during generation of network paths. Successor of an activity form the paths that branch from it. Thus, number of paths which branches of an activity is equal to its successors. For instance, when activity 2 is considered, then path 1/2/ 4 will continue and two new paths will be branched from activity 2. They are paths 1/2/5 and 1/2/8 as shown in Fig.7.

The path matrix is determined by identifying the activities lying on each path. The first activity, which belong to step number 1 and its successors are identified initially. Then, check the activities in increasing order according to their sequence numbers. When the checked activity has more than one successor, then new paths will be appended and their activities will be defined.

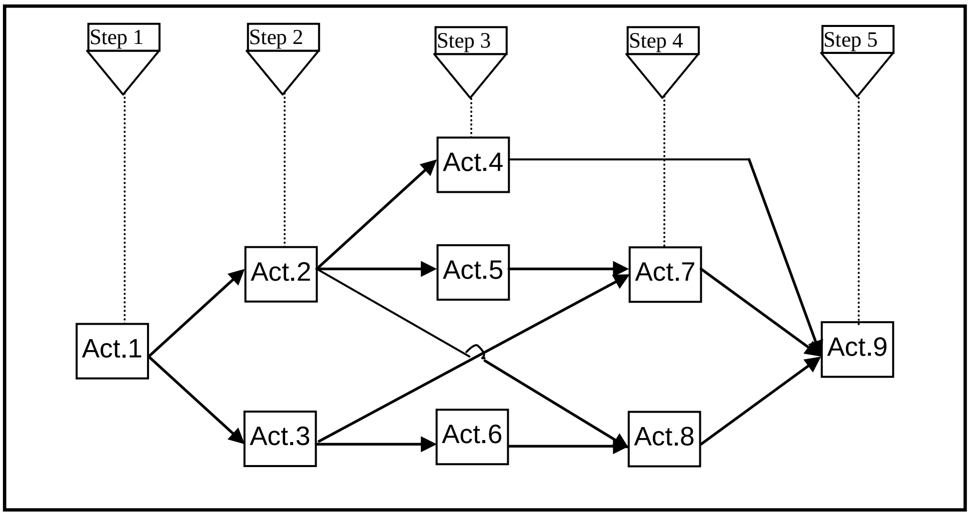


Fig.7 Example Problem for Illustrating Step Numbers

Suppose NS(i) is number of successors of activity i, P(j, i) is the path matrix of the network, and PN is number of paths in the network which can be determined a flow chart. The following steps are used to generate the path matrix:

1. Put all entries of the path matrix equal to zeros; P(j, i) =0.
2. Identify successors of activity 1 and replace corresponding elements in the path matrix by 1. Because, the first activity belong to step number 1 and step numbers of its successors are more than 1, hence, first activity and its successors form the starting point for identifying activities of the path matrix. Therefore, number of paths that is generated by these activities are equal to number of successors of activity 1 in this stage, i.e., PN = NS(1). The following equations will be used:

II= Su(1, j)   j=1, 2, …, NS(1)

P(j, 1) = 1 and P(j, II) = 1   j=1, 2, …, NS(1)

Where, Su(1, j) is successor number j of activity 1.

3. Repeat the following procedure starting with a step number equals 2 and ending with a step number equals $N_{st} - 1$.
4. Check in turn activities of the network, except last one.
5. Consider path j.
6. Check if step number of the considered activity i is identical with the considered step number s and belongs to path j. When this condition is violated, go to step 8. Otherwise continue. It should be noted that if the considered activity i belongs to path j, the entry P(j, i) must equal 1.
7. Continue by identifying other activities of path j. New paths may be generated. Thus, the following sub-steps are performed:

7.1 Define first successor of activity i and append it to the considered path j. It is a continuation of path j. Thus, the column which represents sequence number of first successor of activity i is replaced by 1.

7.2 Calculate number of new paths that may be appended to the existing paths where the considered activity i may have more than one successor. It should be noted that all paths of path matrix are generated in step 1. But, the expression append mean than activities of these path will be identified. The following equation will be used:

$L = NS(i) - 1 \qquad\qquad i = 2, 3, ..., N - 1$

Where, L is number of new paths that will be appended to the existing paths.

7.3 Identify activities of the new paths; L . Activities of the new paths are activities of the considered path j and successors of activity i. Thus, the new paths are supplied by a copy of the considered path from first activity to activity i. In addition, replace the corresponding successors of activity i by 1 on the these paths. It must be pointed that the first successor of the considered activity i is not used on the new paths. It is a continuation of the considered path j as shown in sub-step 7.1.

8. Put j = j+1. If $j \leq PN$ go to step 5. Otherwise continue.
9. Update number of existing paths; PN to include the appended paths in step 7.

Fig. 8 gives flow chart for generating path matrix of the equivalent network.

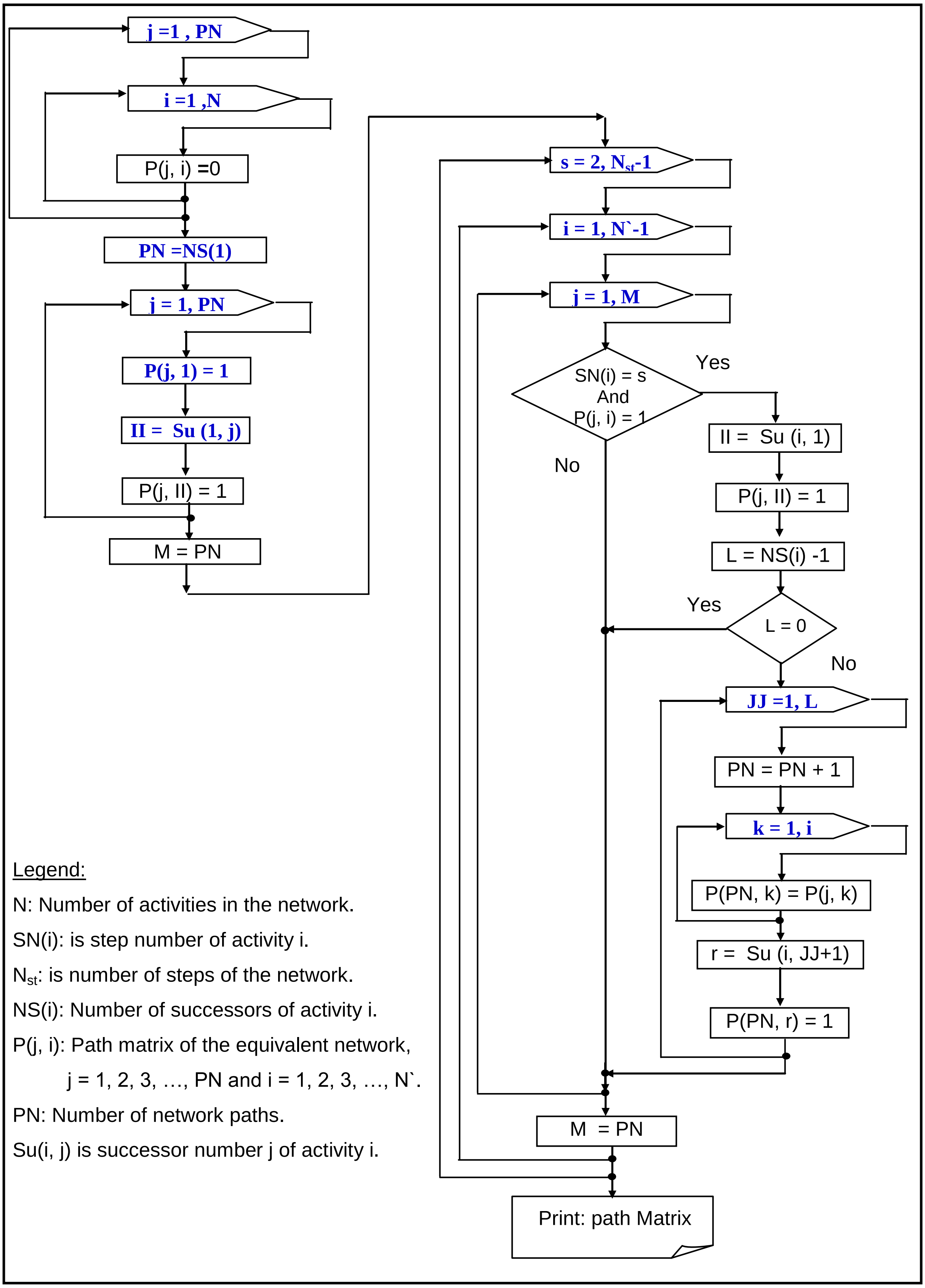


Fig. 8 Flow Chart for Generating Network Paths
A Proposed Technique For Analysis of Delays on multiple Critical Paths

To overcome the problems disused in previous paragraph, the author suggests a new method to analyses delays and work changes on multiple primary critical paths. In this method, the percentage of summation of any type of delays lying on all primary critical paths and the summation of all types of delays lying on all primary critical paths is calculated. This percentage represents the responsibility of the considered type towards total project delay. The percentage for each type of delays will be calculated using the following formula:

$$D\% = \frac{\text{Suming the considered type of delays on all primary critical paths}}{\text{Suming all types of delays on all primary critical paths}}$$

where, D% is the percentage of the considered type of delay towards total project delay. The responsibility of each party towards total project delay can be determined by multiplying this percentage by total project delay as follows:

D = D% * TP

Where, D is number of days with compensable delays or non-excusable delays. and TP is total project delay. For instance, the percent of compensable delays is calculated by dividing the summation of compensable delays along all primary critical paths on the summation of all types of delays on all primary critical paths. Time extension is determined as follows:

Time extension = compensable delays + excusable delays

Excusable delay can be determined using similar previous equations or calculated as the difference between total project delay and summation of compensable and non-excusable delays.

The proposed technique is more reasonable because it considers the importance of all type of delays along all primary critical paths. The proposed technique has the following characteristics:

1. It overcomes all problems, which are discussed in this research.
2. Owner and contractor payments are proportional with their delays along all primary critical paths.
3. It does not cause a dispute between parties because number of compensated days of owner and contractor do not exceed total project delay.
4. It can be used in all cases: one primary critical path, multiple primary critical paths with or without concurrent delays.

An example problem is now used to illustrate the proposed techniques to analysis of concurrent delays using percentage technique. Table 2 gives planning data, while Table 3 gives start and finish dates of each delay.

Table 2 Planning Data of the Example Problem

Activity	As-Planned Duration (Days)	Predecessors
1	2	-
2	5	1
3	4	-
4	7	1
5	6	2
6	3	3, 4
7	9	2
8	4	5, 7
9	8	6
10	5	8, 9

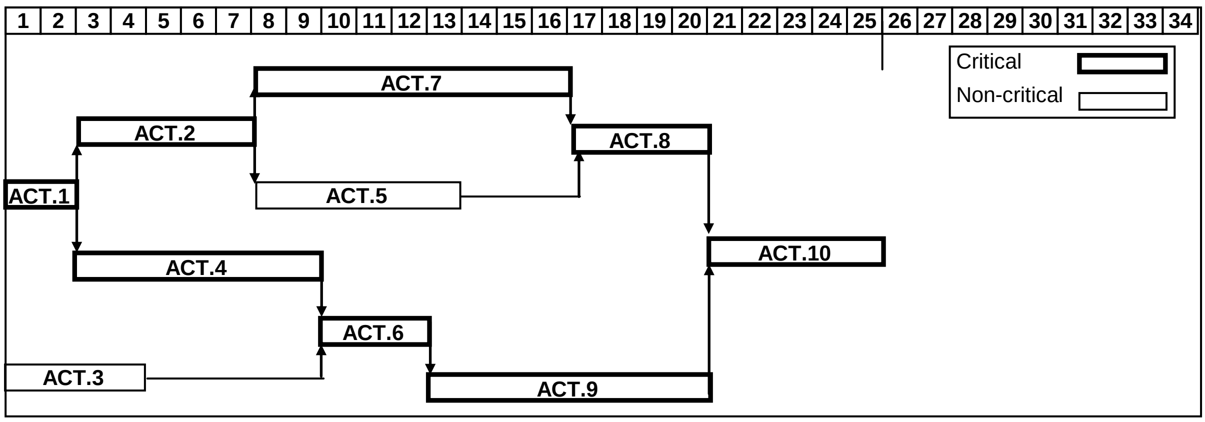
Table 3 Field Report of Delays and Work Changes

No.	Delay type	Activity Affected	Delay start	Delay finish	Delay Time
1	Contractor	2	5	8	4
2	Owner	3	3	7	5
3	Contractor	7	14	15	2
4	Owner	7	20	22	3
5	Owner	5	13	14	2
6	Contractor	5	15	16	2
7	Neither	5	20	22	3
8	Contractor	4	7	9	3
9	Owner	6	13	13	1
10	Neither	6	14	14	1
11	Neither	9	18	18	1
12	Contractor	9	20	22	3

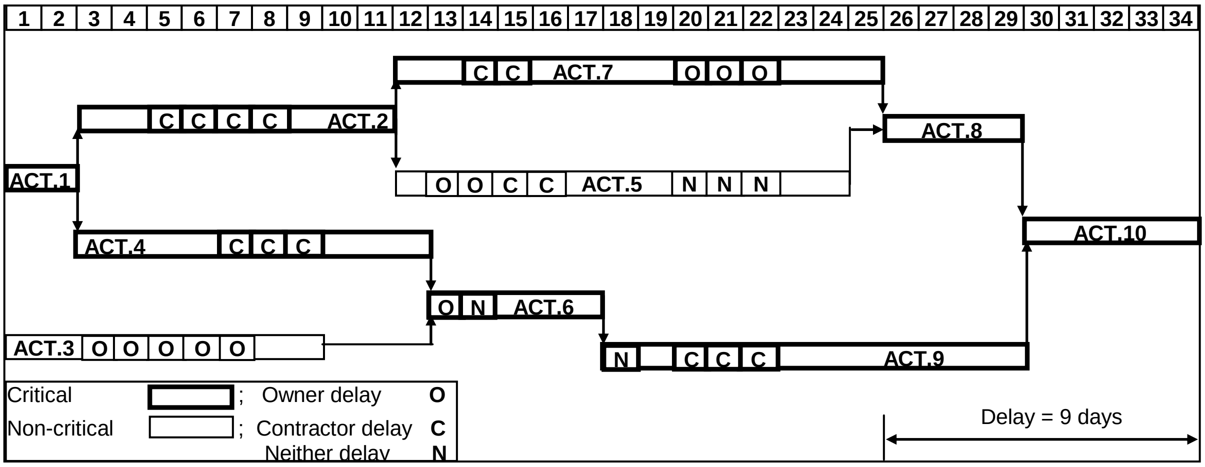
The as-planned schedule comprises four paths:
path 1 (activities 1, 2, 7, 8, and 10), path 2 (activities 1, 2, 5, 8, and 10), path 3 (activities 1, 4, 6, 9, and 10), and path 4 (activities 3, 6, 9, and 10) as shown in Fig.9.a.
The as-planned project completion is 25 days while the as-built project completion is 34 days as shown in Fig.9.b.
Path matrix is generated and gives in Table 4 according the steps shown in Fig.8. The as-planned and as-built schedules contain two critical path (1 and 3) which have longest networking duration.

Table 4 Path Matrix of Example Project As Zero-One Form.

	start	1	2	3	4	5	6	7	8	9	10
Path (1)	1	1	1	0	0	0	0	1	1	0	1
Path (2)	1	1	1	0	0	1	0	0	1	0	1
Path (3)	1	1	0	0	1	0	1	0	0	1	1
Path (4)	1	0	0	3	0	0	1	0	0	1	1



a. As-Planned Schedule



b. As-Built Schedule

Fig.9 As-Planned and As-Built Schedule of the Example problem

The example problem show. is resolved by the percentage method. Therefore, the percentage for each type of delays is determined using the previous equation as follows:

- The percentage of compensable delays

$$D\% = \frac{\text{Suming compensable delays on primary critical paths1 and 3}}{\text{Suming all typesof delays on primary critical paths1 and 3}} = \frac{4}{18}$$

- The percentage of non-excusable delays = $\frac{12}{18}$

- The percentage of excusable delays = $\frac{2}{18}$

The responsibility of each party towards total project delay (TP = 9 days) is determined as follows:

Compensable delays = $\frac{4}{18} \times 9 = 2$ days

Non-excusable delays = $\frac{12}{18} \times 9 = 6$ days

Excusable delays $= \frac{2}{18} \times 9 = 1$ days

Time extension = 2+1 = 3 days

Conclusion and Recommendations:

It is not exceptional to fined different types of delay occur simultaneously on multiple critical paths. These delays are called concurrent delays. The techniques used in concurrent delays analysis are discussed in this research.

Many problems may be encountered during analysis of delays and work changes on multiple critical paths with or without concurrent delays. To overcome all mentioned problems, the author suggests a new method, which is called the percentage method. The proposed technique can be used in all cases: one primary critical path or multiple primary critical paths with or without concurrent delay. The results of the new method are believed to be reasonable and fair. Thus, the proposed model will be based on the percentage method.. In addition, it is assumed that project parties will be fair when dealing with multiple critical paths.

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