

# Impact of Structural Uncertainty on the Time Parameters of the Project Schedule in a Coal Mining Application

Danylo Nazymko

*Université Côte d'Azur, Valrose Avenue 286 06103 Nice, France  
danylo.nazymko@etu.univ-cotedazur.fr*

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**Abstract:** Stochastic Monte Carlo simulation has been used to simulate a mining program schedule in uncertain parametric and structural conditions. Task duration was entered as distributions, reflecting parametric uncertainty. To simulate structural uncertainty, the probability of the task occurrence and the correlation between tasks were considered. The combined effect of these factors was a novel aspect of this research. The probabilities and distributions of the critical path were analyzed as a function of structural and parametric uncertainties. Nonlinear dependences were registered as an effect of the uncertainties. A case study was conducted on an example of a mining program schedule having 107 tasks. This experience confirmed that parametric and structural uncertainties, when combined, can dramatically alter the distribution of the critical path, thereby altering decisions in project management and expediting. Enhancing the sustainability of the coal mining program can be essentially improved by eliminating task correlations and minimizing program structural uncertainties.

## 1 INTRODUCTION

Despite advances in the development of the theory of project management, more than half of them end up with significant delays in project timelines, budget overruns, and cuts in project scope and objectives [1]. The main reason is the turbulent project environment in which parametric and structural uncertainty arises. Naderpour et al. [2] made a systematic literature review and developed a new model for uncertainty management in the time estimation of construction projects.

As early as 1975, Ang, Chaker, and Abdelnour [3] developed a probabilistic network evaluation technique algorithm. They accounted for mean durations and the correlations among the network paths to evaluate the probability distribution of the project completion time. However, they emphasized parametric uncertainty, leaving in a shadow the structural ambiguity as a separate important factor, which may affect the project.

Mahmoudi and Javed [4] upgraded the review of fast-tracking and crashing techniques that project managers usually deploy to speed up the processes and ensure the delivery of projects on time. These two main techniques are considered separate and

relatively independent approaches. However, Nazimko and Zakharova [5] demonstrated that the crashing unavoidably induces and accelerates the fast-tracking effect, increasing the probability of multi-chain critical paths occurrence. This new positive effect exploits the structural uncertainty that was not previously noted.

De Meyer, Loch, and Pich [6] identified four project uncertainty types: variation, foreseen uncertainty, unforeseen uncertainty, and chaos or turbulence. In this paper, the foreseen uncertainty was considered more strictly as the uncertainty in the structural characteristics of a project schedule.

The sensitivity of the project to structural uncertainty may be significantly higher than to parametric uncertainty [5]. Under these circumstances, the management of project structure takes on special importance.

Mining is a typical industry that organizes its activities into projects and even large programs, carried out in uncertain geologic environments.

Task uncertainty may be represented by its probability, which can alter the project schedule structure. Task's interdependence can be expressed through their correlation.

Geological uncertainty can directly affect structural uncertainty, such as task probability.

The elastic and strength parameters of the rock mass significantly affect advance rates and can be treated as stochastic parameters, characterized by a specific distribution within a given range. When determining the longwall face advance rate using the deterministic method, these uncertainties within the rock mass are ignored, making the final result neither accurate nor reliable. Therefore, statistical and probabilistic risk analysis can provide more reliable results.

Increased depths, adverse geological uncertain conditions, elevated variable stress regimes, and weaker ground conditions, coupled with an industry-wide need for higher development rates, continue to make ground control management challenging.

Stochastic modeling is the most powerful tool for studying the structural uncertainty of projects [7].

A stochastic project scheduling model was employed, which takes into account the parametric uncertainty of the project by using any distributions of the tasks' durations as inputs, and the structural uncertainty considering the occurrence probability of scheduling tasks or activities and their correlation [5]. This model was selected because it accounted for multi-chain critical paths and provided an optimal expediting process for a project schedule. All critical paths are equitable items of a project schedule [5]. Furthermore, if the project is deployed in an uncertain environment, the most critical paths may swap places.

Table 1: Input data for the stochastic model.

Task number	Task probability	From node	To node	Duration mode	Minimum	Maximum	Correlated activity	Correlation coefficient
1	2	3	4	5	6	7	8	9
1	1	1	2	20	10	30	0	0
2	1	2	3	20	10	30	0	0
3	1	2	4	20	10	30	0	0
4	1	2	5	20	10	30	0	0
5	1	3	6	20	10	30	0	0
6	1	4	6	20	10	30	0	0
7	1	5	6	20	10	30	0	0
8	1	6	7	20	10	30	0	0

This paper investigates the influence of structural uncertainty on project parameters, addressing a highly relevant problem for understanding the

patterns that can shape project management actions in an uncertain environment.

## 2 DESCRIPTIONS OF THE MODEL (DEMONSTRATIVE EXAMPLE)

Figure 1 shows a calendar graph for a simple, demonstrative project with eight activities. The project graph follows the “activity on the arrows” convention, where “boxed numbers” or nodes represent events, while arrows or arcs represent activities or tasks [8]. The “dashed” arrows (Fig.1) represent activities that can have structural uncertainty, as discussed in the following text. Graph nodes were used to express the logical relationships between tasks, which is very effective in handling strongly correlated tasks.

The graph has a sequential-parallel structure to study the influence of uncertainty factors in both the sequential execution of activities and their simultaneous deployment. According to the Monte Carlo-based algorithm, the same schedule is simulated many times (thousands of times) to obtain a representative set of data points, which are subsequently used for analysis. The required number of simulations is determined using the relevant criterion at a predetermined confidence level.

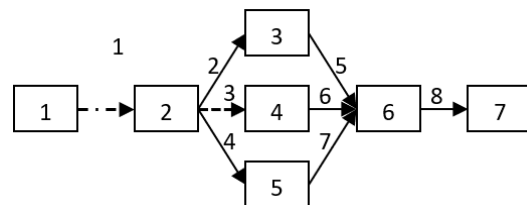


Figure 1: Project schedule graph.

Table 1 presents the input data entered during the stochastic modeling process. Figure 2 shows the histogram of the project completion dates. With a deterministic formulation of the problem and using the modal durations as inputs, the total project duration would be 80 days.

However, the most probable project completion date for the stochastic variant is  $85 \pm 7.28$  days, whereas the most optimistic project completion time varies between  $58 \pm 8$  days. The distributions of task completion times exhibit an approximately symmetric form and align well with the normal distribution, as was proved with the Shapiro-Wilk criterion [9].

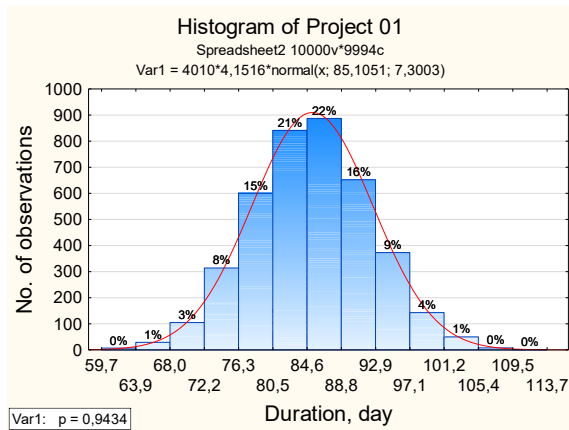


Figure 2: Project duration distribution.

Special experiments have shown that regardless of the shape of the distribution of input parameters, at the output, the experimental data points are approaching a normal distribution, which agrees with the central limit theorem [10] and demonstrates the validity of stochastic modeling results.

A whole set of critical paths has been obtained because there are a large number of possible variants and combinations of initial factors in the process of stochastic modeling. Furthermore, the larger the graph of the project schedule, the greater the number of possible critical paths [5]. Therefore, even for a small representation, seven critical paths were obtained, as shown in Table 2.

Table 2: Critical path frequencies.

Critical path (tasks)	Frequency
1-2-5-8	0.317
1-3-6-8	0.306
1-4-7-8	0.302
1-3-6-8    1-4-7-8	0.027
1-2-5-8    1-4-7-8	0.022
1-2-5-8    1-3-6-8	0.022
1-2-5-8    1-3-6-8    1-4-7-8	0.003

Since all initial deadlines were set equally, the main critical paths ran through the chains of tasks 1-2-5-8, 1-3-6-8, and 1-4-7-8, and their probabilities were approximately 0.3. Due to the probabilistic nature of usual processes, reflected in the stochastic model as distributions of input factors, parallel critical paths emerged from random arrangements. These paths are rarely encountered in the deterministic formulation of the problem. Thus, with probability 0.022-0.027, the critical path can pass simultaneously through all possible combinations of pairs of nodes 3 and 4, 3 and 5, or 4 and 5. The critical path passes through all three parallel nodes 3, 4, and

5 with a probability of 0.003. This regularity was documented by Nazimko and Zakharova [5], who proved the importance of taking into account multi-chain critical paths.

### 3 INVESTIGATIONS OF THE STRUCTURAL UNCERTAINTY

#### 3.1 Task Probability Effect

The influence of the schedule structure on the uncertainty in the project parameters of the base model was studied. For example, the probability of task 3 passing through nodes 2 and 4 was set to 0.5. This means that in about 2000 cases out of 4000 iterations, task 3 will be absent (as indicated in Fig. 1 by a dashed arrow), and the graph structure will change. It turned out that the overall project completion dates have not changed much despite the aleatoric presence of task 3 in the calendar. Thus, the mode of the project end date is  $84 \pm 7.4$  days. According to the Kolmogorov-Smirnov criterion, the difference in terms compared to the full graph of the project was insignificant.

Table 3: Frequencies of critical paths.

Critical path (tasks)	Frequency
1-4-7-8	0.397
1-2-5-8	0.384
1-3-6-8	0.155
1-2-5-8    1-4-7-8	0.038
1-2-5-8    1-3-6-8	0.013
1-3-6-8    1-4-7-8	0.010
1-2-5-8    1-3-6-8    1-4-7-8	0.002

However, a significant difference was observed in the probabilities of critical paths (Table 3). Thus, Table 3 shows that the frequency of the critical path 1-3-6-8 has decreased by about half, while the frequencies of the two remaining parallel paths, 1-2-5-8 and 1-4-7-8, have noticeably increased. Notably, all other less probable paths that include node 4, through which task 3 passed, significantly decreased their probability to about 1%, while the path 1-2-5-8 || 1-4-7-8, which does not have this node, significantly increased the frequency of its occurrence to 0.038. The reason for this effect is that the function of the temporarily absent task 3 was taken over by tasks 2 and 4. Consequently, it was possible to conclude that reducing the probability of tasks on parallel chains in the project schedule graph does not affect the overall value of the project execution time. This only reduces

the probability of passing through the critical path when there is a task with a decreasing probability along the chain.

It should be assumed that removing a task from the sequential chain will have a different effect. To test this assumption, the probability of 0.5 was now given to task 1 (marked by the dashed-dotted vector in Fig. 1). The other tasks had a probability equal to one. The distribution of critical paths and their probabilities was approximately the same as in the first variant since the symmetry of the graph was not broken in this variant. Therefore, the span of the whole project has significantly decreased, namely, the mode of the project execution time became  $75.3 \pm 11.5$  days, or reduced by 10 days. At the same time, the project span has increased by 1.6 times. Thus, the decrease in the probability of the schedule's tasks on its consecutive chains diminishes the project's average span but increases its variation.

### 3.2 Effect of Tasks Correlation

One of the most important characteristics of the project schedule structure is the mutual dependence between activities, which is another structure parameter. Table 4 shows the results of the stochastic simulation for a symmetric correlation between the durations of activities 2 and 4. Both positive and negative correlations were investigated with a correlation coefficient of  $\pm 0.8$ .

It turned out that the effect of task interdependence does not depend on the sign of the correlation. In addition, the project completion time and its variation do not change, regardless of whether there is a correlation between the activities. The effect of mutual dependence between activities affects primarily the probabilities of the critical paths to which the correlated activities belong. This is clearly demonstrated in Table 4, where the critical path 1-2-5-8, containing task 2, and the path 1-4-7-8, containing task 4, significantly increased their probability to 0.33-0.36, while the path 1-3-6-8, not containing correlated tasks, significantly decreased its frequency of occurrence. The same can be said of paths with low probability.

Table 4: Critical path frequencies.

Critical path (tasks)	Frequency
1-4-7-8	0.355
1-2-5-8	0.338
1-3-6-8    1-4-7-8	0.038
1-3-6-8	0.230
1-2-5-8    1-3-6-8	0.023
1-2-5-8    1-4-7-8	0.018

## 4 CASE STUDY

### 4.1 Description of a Mining Development Program

The variants of the year program schedule were analyzed in the case of mining development in a large Ukrainian coal mine. This mine produces coking coal, which is an important source for Ukrainian steelmaking and defense. The productive seam is mined at depths of 950-1100 meters under difficult mining and geological conditions. The coal seam is extracted using longwall technology, with full caving of the roof as the ground control. Methane content in the coal seam ranges from 8 to 15 m<sup>3</sup>/ton, which impedes longwall ventilation and necessitates maintaining sustainable underground stability of the roadways.

The initial data file, which digitally outlines the program of 107 real underground mining activities, is shown in [11]. The duration of tasks in this case was expressed in weeks. The longwall faces were planned to provide 6,840 thousand tons of raw coal during the planning period. Parametric uncertainty was accounted for by using a normal distribution for task durations. Structural uncertainty was described by the probability of tasks and their correlations.

The basic mining tasks were considered, namely longwall extraction (14 tasks) and development of the reserves or roadways and entries driving (93 tasks). Other auxiliary tasks, such as construction, transportation, ventilation, and power supply, were outside the scope of this project. In fact, it was a megaproject or program, because even extracting a panel or driving a 3-kilometer-long roadway is a significant project.

The process of modeling the annual mining development program has been carried out iteratively. To determine the program schedule's critical path, 5,000 iterations were used. In each iteration, the computer selected random values for the task rates based on predetermined distribution laws derived from previous mining activity experience.

At each iteration, the critical path was determined, and all characteristics of each task were stored in a special file: its duration, earliest and latest start and end dates, and free time reserve. During the iterations, critical paths were tracked, and their occurrences were counted. At the end of the simulation, the frequencies of all critical paths were calculated, reflecting their probabilities with a predetermined level of reliability. The more iterations, the closer the frequency aligns with the actual probability.

## 4.2 Investigation of the Tasks' Probability and Their Correlation Effect

Three variants of the mining development program were simulated. In the first variant, the probability of all activities was equal to one, and there was no dependence between activities [11]. In the second variant, the probability of task 88 (1<sup>st</sup> south entry, block 10, duration mode=40 weeks) was set at 0.5.

The technologies used to prepare the panel for coal extraction can vary significantly depending on whether a low-amplitude transient disturbance occurs. This is precisely the situation with the development of a panel that consists of tasks 88-89 (1<sup>st</sup> and 2<sup>nd</sup> south entry block 10, duration mode=40+8=48 weeks). Therefore, the structural uncertainty of the schedule was accounted for with a probability of 0.5 in the second version of the model. This means that if a low-amplitude fault is present and cannot be passed by the longwall, a pillar should be left around the fault, and two separate longwalls will be required. Consequently, two startup rooms and the first south entry (task 88) will be needed. However, if the low-amplitude fault is not problematic and can be bypassed, the panel will be extracted using a single longwall.

Often, the activities depend on each other. This is especially true in underground coal mining. A typical example is when two underground roadways share a single source of fresh air for ventilation during their development. This is exactly the situation that occurred during the development of two roadways, tasks 88-89 and 90 (north ventilation roadway, horizon 708 m, duration mode=48 weeks). The extraction of coal seams at a depth of 1000 meters is accompanied by an intensive release of explosive methane. Therefore, its concentration should be maintained at a safe level, not exceeding 1%. Hence, both ventilation roadways and the 1<sup>st</sup> south entry draw fresh air from the same source: the roadway that supplies it. Thus, there was an inverse relationship between the consumption of fresh air: the more air consumed by one production unit, the less air is left for the other, and vice versa. Accordingly, the rate of development of the roadways changed in proportion to the consumption of fresh air. This inverse-proportionality dependence is taken into account by the correlation between the rates of 88-89 and 90 task realizations. The correlation coefficient was -0.95. This difference characterized the third variant of the schedule model.

The finish of the last program variant ranged from 45 to 135 weeks, with the most likely being 77 weeks. Table 5 lists the most likely critical paths for all program schedule variants. The program contains both sequential and parallel paths.

A total of 34 critical paths were detected, both sequential and parallel. Only activities with a frequency or probability greater than 0.05 were selected. In the first variant of the program schedule, the total frequency of six such significant critical paths was 0.596, with the maximum frequency of path 66-67 (duration mode = 41 + 7 = 48 weeks) being 0.163.

In the second option, the number of critical paths increased to eight, with the most likely critical path remaining 66-67. The probability of path 88-89 decreased by about half, which corresponds to a structural probability coefficient of 0.5 [11]. Critical path 88-89 gave way to paths 41-42-43 (duration mode = 22 + 14 + 12 = 48 weeks) and 90, which made it possible to enter the number of significant critical paths. It is noteworthy that the total probability of significant critical paths increased to 0.662 or 11% compared to the first version of the program schedule.

However, the most significant changes occurred in the third variant. In this case, the correlation of pathways 88-89 and 90 led to a change in leaders, as critical pathway 88-89 became the most likely. At the same time, the dependent critical path 90 became a component of the significant ones, and as a result, it took second place in the list. It should be noted that in the first version, it was completely absent, and in the second version, it barely exceeded the level of 0.05.

Now its frequency has increased four times and amounts to 0.248. These two pathways removed almost all critical pathways with probability less than 0.1 from the list, and the former leader, 66-67, barely managed to stay on the list.

Even though the number of critical paths in the third variant is minimal, their total probability has increased to the highest level, up 33% compared to the first variant. Thus, a nonlinear dependence of the program schedule structure on parameters such as path probability and their correlation was observed. Not only did the probability of critical paths change, but also their positions in the list of more significant critical paths. Both the decrease in task probabilities and the increase in their correlation negatively affect the project schedule, reducing its balance and increasing differences among the critical paths' probabilities.

Table 5: The most likely critical paths.

1 <sup>st</sup> variant		2 <sup>nd</sup> variant (Probability of 88=0.5)		3 <sup>rd</sup> variant (Correlation 88-89/90)	
CP	Probability	CP	Probability	CP	Probability
66-67	0.163	66-67	0.169	88-89	0.423
88-89	0.159	68	0.085	90	0.248
27-28-29	0.078	76-77	0.083	85-86-87	0.071
68	0.076	88-89	0.083	66-67	0.053
76-77	0.067	27-28-29	0.08		
46-47-48-49	0.053	46-47-48-49	0.057		
		41-42-43	0.053		
		90	0.052		
Total	0.596		0.662		0.795

According to [5], the greater the number of multiple critical paths and the closer their probabilities, the more balanced the project schedule becomes. This point was further elaborated by a new finding: the likelihood that tasks take less than one unit of time and the correlations between tasks are the most influential factors contributing to project delay risks and complicating the expediting process. Besides, it was shown that decreasing the probability of tasks in parallel chains does not affect overall project duration, but it lowers the chance that those chains become critical paths. In addition, reducing the probability of activities in sequential chains shortens project duration but increases variability.

Another new finding showed that the effect of task interdependence on project parameters is independent of the sign of the correlation. Project duration and variability also remain unchanged regardless of whether tasks are correlated. However, correlations between tasks increase the probability of critical paths in the affected chains. Changes were observed in both the probabilities of critical paths and their ranking among the significant critical paths.

From a practical standpoint, it is important to avoid combining unlikely tasks with correlated tasks.

### 4.3 Effect of Structural Uncertainty on Expediting Process

The deployment of expediting is a common measure to ensure a program meets its due date or at least to

reduce delays. The mining program was conducted for two scenarios: one without structural uncertainty and one with structural uncertainty. According to [8], [5], the process of crushing from the most critical task 66 located on the most critical path 66-67 (refer to Table 5, 1st variant) was started. The reduction of task duration was carried out in small increments, with each cut being no more than one week of the task duration. Then a new set of critical paths was found, and expediting iteration was repeated. Such an iterative approach ensured an optimal path of the expediting evolution because this irreversible process was path-dependent.

Table 6 demonstrates essential differences in the list of critical paths during the program's expediting. Four iterations have been needed to finish the expediting process for 1<sup>st</sup> variant and minimize the critical path frequency to 0.1. The further expediting made no sense because any of the critical paths 77-76, 121-28-29, or 46-47-48-49 showed approximately the same probability. On the contrary, twice as many iterations were needed to accomplish expediting the program with correlated tasks. The process of compressing the critical paths began with path 88-89, where tasks 88 and 90 were correlated. Task 88 was modified in the first iteration, changing the most probable critical path to 90.

This path prevailed from the second iteration until the seventh. The frequency of the critical task 90 was reducing slowly. At last, it approximately matched the frequency of tasks' sequence 88-89 (0.16≈0.10).

Table 6: Critical paths evolution during expediting.

Iteration	No correlation							
	1	2	3	4	5	6		
Critical path	66-67	88-89	88-89	77-76	121-28-29	46-47-48-49		
Frequency	0.163	0.208	0.156	0.1	0.098	0.096		
Iteration	Correlated tasks							
	1	2	3	4	5	6	7	8
Critical path	88-89	90	90	90	90	90	90	66-67
Frequency	0.423	0.454	0.458	0.386	0.312	0.206	0.176	0.16(0.11)

Further expediting was not expedient because several critical paths leveled their frequencies [5] (Fig. 3). The curves in Figure 3 represent the frequency of critical paths, which consisted of different tasks and replaced each other during the expediting processes (refer to Table 6).

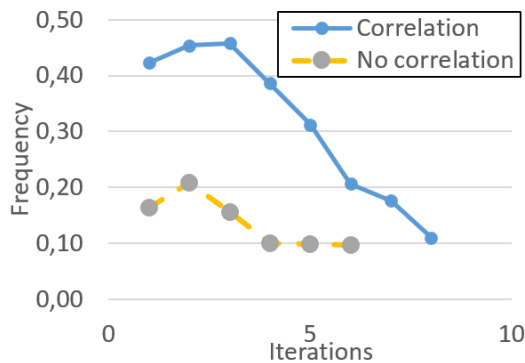


Figure 3: Frequency of critical paths variation.

This experiment has shown that structural uncertainty may essentially delay the process of expediting the mining development program.

To reduce the risk of program delays, the following two measures have been proposed to control the program schedule's structural uncertainty.

Firstly, operators should apply microseismic tomography to clarify low-amplitude faults in the coal seam [12], [13]. This will reduce the geological uncertainty and increase the probability of an underground roadway driving in a disturbed coal seam. The risk of economic losses from the loss of a mechanized complex is three orders of magnitude higher than the cost of seismic tomography.

Secondly, operators should provide an independent ventilation source for tasks 88 and 90 to eliminate the correlation between the two roadways.

As the project progresses, discrepancies between the plan and reality emerge, often requiring the originally single critical path to be crashed [5]. Expediting is frequently done in haste, leading to impulsive, ill-considered decisions. This common issue degrades project quality, causes engineering stagnation, and may even lead to safety violations, particularly in the mining industry.

Our model enables agile assessment of the project schedule. If the schedule has a single critical path, it should be redesigned by restructuring it to split some chains into parallel sequences. When multiple critical paths exist, their frequency should be analyzed. If the variance in critical path frequencies exceeds a reasonable threshold (e.g., 20–30%), iterative crashing should be applied as described earlier [5].

Throughout project execution, periodic schedule assessments should be performed using a combination of earned value management protocols [14] and the results of this investigation. The earned value management detects early signs of schedule delays, while the revealed negative effect of correlation facilitates the search for the optimal strategy for project acceleration.

## 5 CONCLUSIONS

Stochastic modeling on project networks is a rather effective tool for investigating the structural uncertainty of a project that is implemented in a turbulent environment. The following conclusions can be drawn:

- 1) The probability of tasks being less than one and the correlation between tasks are the most influential factors that cause the risk of project delays and complicate the expediting process.
- 2) Decreasing the probability of tasks being in parallel chains of the project schedule structure does not affect the overall project delivery time, but only decreases the probability of a critical path through a chain where there is a task that has a decreasing probability.
- 3) Reducing the probability of activities on sequential chains diminishes the project execution time but increases its variation.
- 4) The effect of the mutual dependence of tasks on project parameters does not depend on the sign of correlation. The project span and its variation also do not change, regardless of whether there is a correlation between the tasks. However, the probability of critical paths increases where correlated tasks are located.
- 5) Changes were observed both in the probabilities of the critical paths and in their positions within the list of significant critical paths.
- 6) When developing the program schedule structure, one should be cautious and possibly avoid combining unlikely tasks and their correlation.

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