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Construction Duration and Cost Simulation via Network-Program-Diagram

Abstract This paper outlines the creation of a simulation model used to extrapolate duration and resource requirements needed for the construction of bridges based on a sampling of data obtained during a field research conducted on the construction process of a single bridge. A sampling of statistical data was taken during a field investigation to measure schedule and resource requirements (labor, raw materials and machinery) at various stages of a bridge construction project. This data was used to identify the probability distribution and the associated parameters for the project examined, and a simulation model was built to extrapolate the necessary schedule and resource requirements needed for various stages of similar bridge projects based on Three-Point Estimation Method of Program Evaluation and Review Technique (PERT) and Monte Carlo Method. This simulation model's resultant data for every process in an applicable construction project can be aggregated to form overall project duration and resource requirement statistical distribution using the Critical Path Method (CPM). The whole construction process will be visualized by a 4-dimensional (4D) model of the project which is created by appending time and resource requirements and to the 3-dimensional (3D) model that is built using the Building Information Modeling (BIM) and Alternativa 3D technology. Based on the simulation results of every procedure's duration and resource requirements, the Network Program Diagram and Gantt Chart can be drawn

with Flex and ActionScript language. Furthermore, with the Network Program Diagram at the core, the 4D model can incorporate simulation's resultant data with respect to total time and cost of the project to show the condition of resource requirements and the project's progressing at any time.

Keywords: construction duration, construction cost, activity-on-node diagram, building information modeling

1 Introduction

To confirm construction duration and cost using a simulation method is relatively difficult because it requires synthesis of construction technology, project budget, economics, management, engineering mathematics and modern information technology, and literature concerning this research is limited in scope (Chau, Anson, & Zhang, 2003; Chou, 2011; Ding et al., 2012; Heesom & Mahdjoubi, 2004; Ma, Shen, & Zhang, 2005; Zhong et al., 2003). Because of these characteristics, this area requires research that is predictive in nature. It is difficult to conduct the research based on all construction projects of a whole railway line. Therefore, based on a continuous girder bridge that is part of a passenger railway, the paper supposes to conduct a preliminary exploratory study to extrapolate construction duration and cost using a simulation method.

First, according to the theory of WBS (Work Breakdown Structure) (Golpayegani & Emamizadeh, 2007; Jung & Woo, 2004), this paper decomposes the construction processes of the proposed bridge into multiple process units according to the Network Program Diagram (NPD). The total construction duration is the sum of working hours of all processes in the critical path of the Network Program Diagram, and the direct expense of the project is the sum of resource consumption — including labor, raw material, and machinery — of every individual process. Consequently, the simulation process to estimate total construction duration and expense is broken down into two steps: ① simulating the construction duration and expense of every individual process; ② combining the resultant data for every process according to the Network

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Program Diagram to complete the simulation.

Second, in order to intuitively display variations in process durations and costs and meet the requirements of duration and cost control in the process, this paper, using the Building Information Modeling (BIM) theory (Dino et al., 2009; Steel & Drogemuller, 2012; Yan et al., 2011), constructs a 3D model based on the project. This model realizes virtual construction of project processes based on the Network Program Diagram and relies on the project for additional information on construction duration and resources consumed at each stage of the project. During the construction process, planned and actual consumption of time and resources are input into model, and the difference between the actual and the planned construction process is visually demonstrated, which makes it convenient for project managers to take action in a timely manner to ensure that the project is implemented smoothly.

Obviously, the Network Program Diagram has the core driving effect on the simulation of construction duration and expenses for two reasons: ① The statistical calculation of construction duration and expenses is based on the Network Program Diagram; ② the order of virtual construction is also determined by Network Program Diagram.

In conclusion, the basic structure of the research is presented in *Figure 1*.

2 Analysis and simulation of duration and costs

2.1 Construction duration analysis

The Critical Path Method (CPM) and Program Evaluation and Review Technique (PERT) are two widely used methods to simulate construction duration on the basis of the Network Program Diagram. CPM, which adopts single time estima-

tion technique, recognizes the duration of every process as a definite value in the Network Program Diagram (Kelley, 1961; Kelley & Walker, 1959). However, it is difficult to reflect the fact simply using CPM to analyze the construction duration since, in practice, the duration has a fluctuation range in each process. Also, it is hard to be certain of the critical path of the whole project network when operation time fluctuates in each process. To account for the uncertainty of each process's duration (Clark, 1962; Hahn, 2007; Malcolm, Roseboom, Clark, & Fazar, 1959), PERT assumes each process duration following certain mathematical distributions and adopts the Three-Point Estimation Method to calculate the duration of processes by an expected value, and regards this value a reflection of inherent uncertainty. The total project duration is prone to a degree of uncertainty because of the uncertainty within each individual process. Because PERT considers every process to be isolated, the total construction time is normally distributed according to the Central Limit Theorem.

CPM and PERT are utilized to simulate construction duration in this paper. The steps of simulation are shown as follows.

(1) Investigate and analyze the operation time of each process. Completing equal project quantity under the same condition requires consideration of the two following principles: ① For construction enterprises of different technical levels, the operation time of the same process will be different; ② for construction enterprises of the equal technical level, the operation time of the same process will be different because of some accidental factors during the process of working. Therefore, it is necessary to investigate and analyze the distribution of the operation time of each process, and find the average operation time. In project processing management, this is a research procedure to transform the uncertainty to the certainty.

(2) Calculate the total construction duration. Draw the

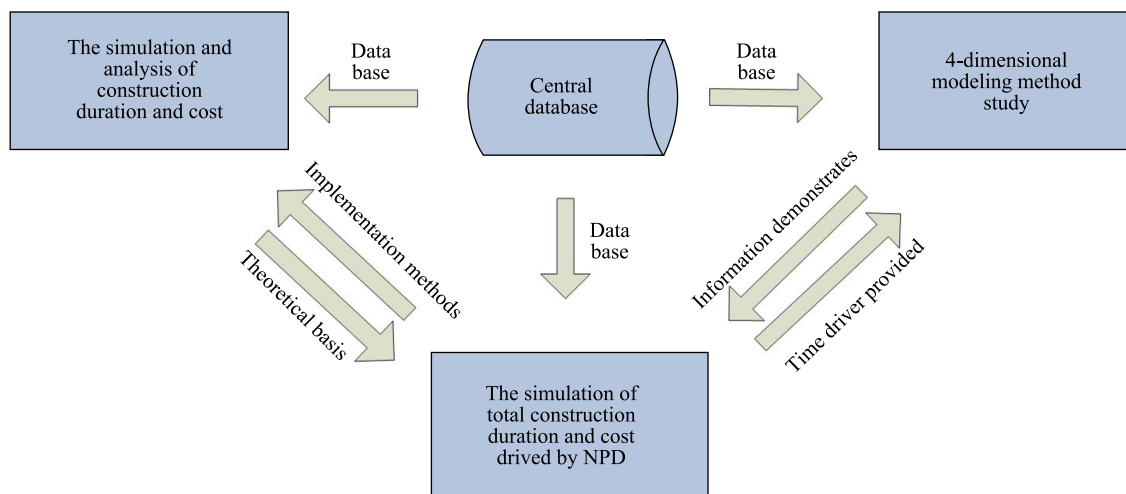


Figure 1. Basic framework of the research.

Network Program Diagram of the project according to how construction is organized. The critical path and critical processes will be determined through the logical relation reflected by this diagram. Calculate the mathematical distribution of construction duration by using the distribution of each individual process and the Monte Carlo Method. The total duration of the project and the probability of this duration of the project are then estimated.

2.2 Construction cost analysis

2.2.1 Expenditure composing analysis

In the traditional construction expense system, quotas take a significant guiding role. According to the factors of production, project quotas can be divided into labor quotas, material consumption norms and machinery one-shift quota, as basic ones to reflect basic necessary factors of production which are needed to produce qualified products directly. The Methodology of Estimate (definitive estimate) Making for Engineering Design of Railway Capital Construction provides that construction installation cost of static investment is made up of direct fees, indirect fees and taxes. The direct fees contain four parts: direct project costs, construction costs, special construction adding fees, large temporary facilities and interim engineering costs. In the calculation procedure of estimates (definitive estimate) for construction and installation works, the quota direct project cost is composed of three parts: base period labor cost, base period material cost, and base period construction machinery use cost. The construction measure cost and indirect cost are equal to the sum of base period labor cost and base period construction machinery use cost times a certain rate.

On the basis of the analysis above, in the procedure of simulation, the labor cost, the material cost and the construction mechanical use cost are the three main parts for calculating the direct engineering cost.

2.2.2 Analysis methods

Practical construction expenses are related to the construction program, the engineering environment and the project management level, and the value has a fluctuating range centered on the social average construction cost standard. It is necessary to adopt the appropriate method for investigation and analysis to calculate the distribution of resource consumption of various levels of society.

Through the data collection, we adopt the Activity Based Costing Method (ABC) (Kaplan & Anderson, 2004) to analyze resource information (labor, materials & machinery) of different construction enterprises in each construction process. Because of the relatively fixed costs of materials and machinery one-shift, research focuses on analyzing the expense of labor. Researching labor expense is similar to researching construction processes. This research requires collecting the numerous samples, calculating the minimum

amount of labor that each process requires, and determining the mathematical distribution and parameters of labor quantity in each construction process.

2.2.3 The determination of mathematical distribution of total construction duration and expenses

In order to determine the mathematical distribution of the total construction duration and cost, there should be large amounts of data on working procedure duration and samples of labor quantity. It is much too expensive to adopt the method of field investigation to all samples. Therefore, by using the Monte Carlo Method (Al-Bahar & Crandall, 1990; Azevedo & Oliveira, 2012; Cox, 1995), the research achieves large necessary samples with the help of computer statistical simulation.

When adopting the Monte Carlo Method to simulate, first, investigate each process's labor quantity and working hours (including the optimistic value, pessimistic value, and the probable value); second, determine the types of mathematical distribution of working hours and labor quantity according to survey results; third, do random statistical tests on working hours and labor quantity in each construction process. The distribution of total labor quantity is calculated using the Network Program Diagram and the probability distribution of total construction duration is obtained by using the CPM method. The process of the simulation of total duration and labor is shown as *Figure 2*.

Similarly, from the mathematical perspective, the material consumption in engineering and machinery one-shift cost can also be simulated by the process presented in *Figure 2*. Then the probability distribution of material consumption and machinery one-shift cost can be calculated. Material and mechanical consumption are mainly determined by engineering contents (construction type and the engineering quantity), it does not have the obvious variation in the material and mechanical consumption as in engineering practice. According to the labor quantity, material consumption and machinery one-shift cost, the probability distribution of direct engineering cost can be calculated.

3 Four-dimensional(4D) data modeling

With the combination of research cost, construction duration simulation and 3D bridge model, the resource cost and the construction duration information will be presented at the same time as the virtual engineering model is constructed (Ding et al., 2012). This model has two aspects: building the 3D bridge model and dynamically presenting the 4D bridge construction.

3.1 Establishing bridge 3D model

Based on the bridge construction chart, adopt the Alternativa 3D engine to produce each bridge part, itemized component

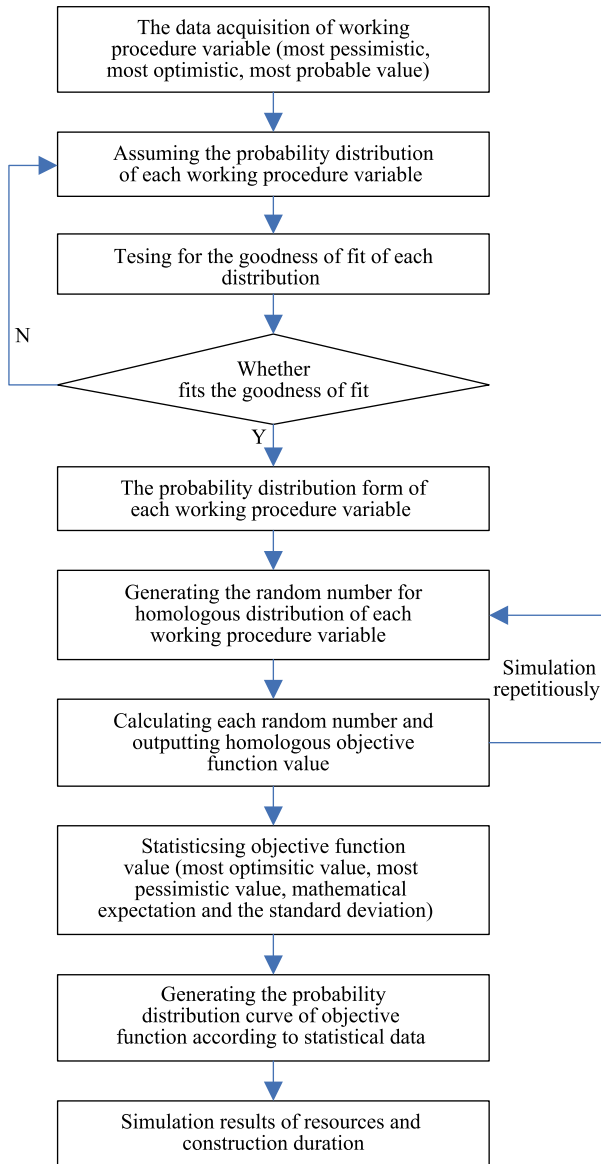


Figure 2. The flow chart of Monte Carlo simulation for total construction time and resource consumption.

template, rebar and the 3D model after cast molding.

3.2 4D bridge construction dynamic presentation

After establishing the 3D bridge model, the contents mentioned above — the expenses and the simulated result of construction duration — should be used to add the schedule information, resource consumption and the construction expense to every structural component. Finally, the bridge 4D model with engineering information will be formed (see Figure 3).

The bridge construction dynamic presentation, which constructed based on the Network Program Diagram, makes a certain work day (generally, the construction duration for

parts of the project is 3 to 7 days) a simulated step, adds every part of the model, subsection engineering structure of the bridge to the scene one by one, finally forming a dynamic construction visual effect. At the same time, the itemize engineering construction duration, the costs, the mechanical and mainly material consumption will be presented. The time axis can be dragged to check the related construction information and the engineering information as needed, and users can click on a certain time point to check the engineering construction information of a certain point in time (see Figure 4).

The dynamic presentation of 4D bridge model overcomes the drawbacks of the traditional static bridge construction management, including poor visualization and lower efficiency of information research, among other factors. It makes the construction cost and schedule management more visual and convenient.

4 Research on total construction duration and cost simulation driven by construction Network Program Diagram

At present, there are many commercial project management software options that can compile Network Program Diagram. However, this research uses the Network Program Diagram to drive construction of a duration and cost simulation and a 4D bridge model demo. In other words, the intrinsic relationship between construction duration and cost analogue simulation and 4D bridge model demo should rely on Network Program Diagram to complete. Obviously, commercial project management cannot fulfill the task. Therefore, compiling a construction Network Program Diagram is the emphasis of this research. The information above (analysis and simulation of duration and cost) can be applied using the following process: compile a Network Program Diagram automatically; then dynamically filter critical paths and simultaneously calculate total duration at every turn; last, obtain the most probable value of total duration according to the probability, generate the Network Program Diagram and Gantt Chart based on the final result of the duration simulation, and perform the cost simulation at the same time.

In addition, the 3D bridge model, which is driven by construction durations, forms animated presentations when combined with the Network Program Diagram.

4.1 The compilation of construction Network Program Diagram and Gantt Chart

The model is divided into three sections: process editing, Network Program Diagram compilation and Gantt Chart compilation (see Figure 5). Process editing is used to compile and demonstrate the data of each process. The Network Program Diagram and Gantt Chart demonstrate resource consumption and rate of progress. Process editing and Network Program Diagram and Gantt Chart development are

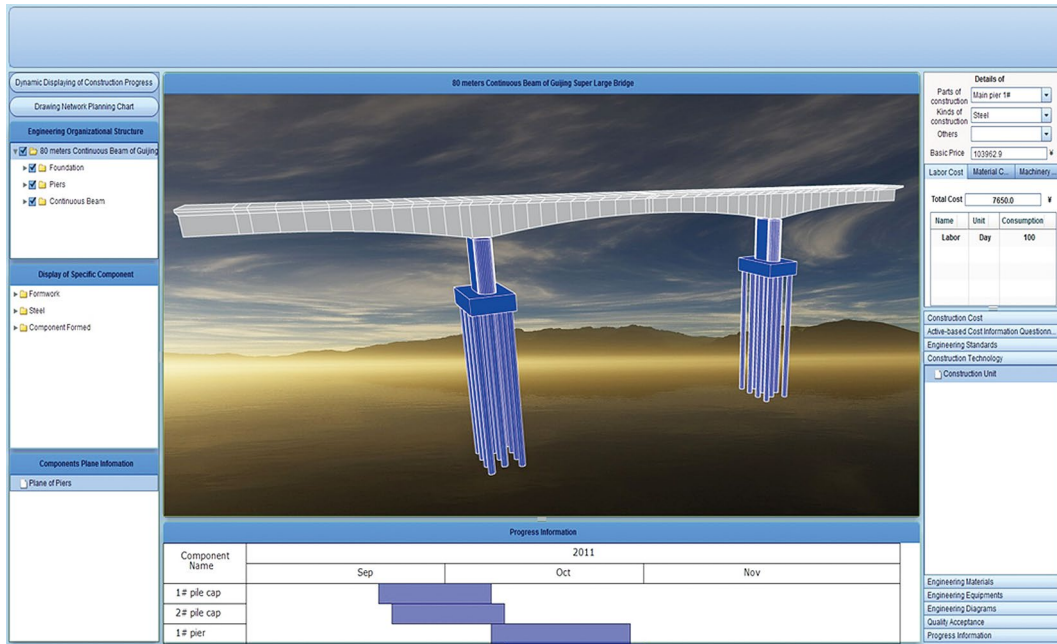


Figure 3. 4D bridge model.

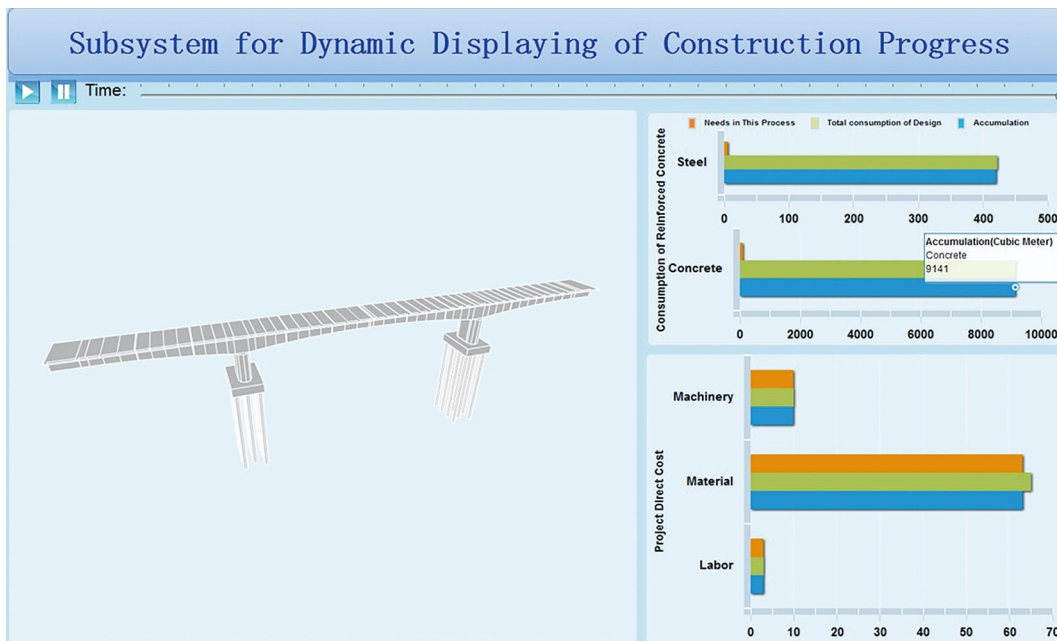


Figure 4. Dynamic demo of construction process.

all based on a unified, central database, and they all achieve dynamic joint action.

4.2 Technical support

While the front end of the system is designed with Flex, the back end uses Java to communicate with the database.

In the stage of process editing, data in a spreadsheet serves to enable the compilation and demonstration of

database. Adopt persistence layer framework Hibernate technology to complete the communication between Java and data in the database, in order to ensure the completion of content of interface compilation, and quickly deliver data to background database, and meanwhile, keep coordination between them.

Graphic components generated by Action Script insert an interface to form a Network Program Diagram and Gantt Chart. The Network Program Diagram is the foundation

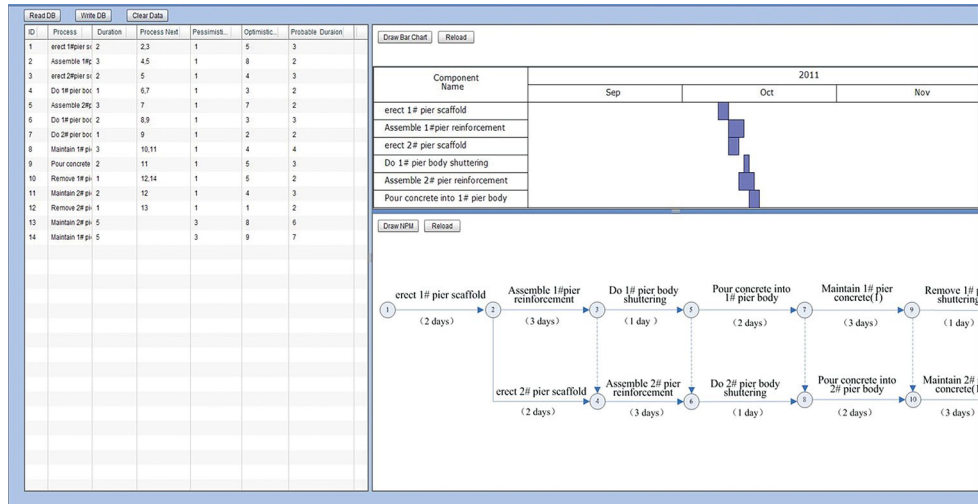


Figure 5. Network planning diagram and Gantt Chart compilation.

of the Gantt Chart and one traversal of the whole Network Program Diagram is enough to draw the Gantt Chart.

5 Analogue simulation based on a project case

Take duration simulation of 1# and 2# piers of a continuous girder bridge (48 m + 80 m + 48 m) in the Xiamen—Shen-

zhen passenger railway for example. According to the field survey of each construction process of these piers, determine temporal distribution and parameters of each construction process (see Table 1).

Adopt the Monte Carlo Method and definite mathematics distribution to take vast random sampling in construction duration of each process. Total duration is equal to construction duration of each process on the critical path. According to simulation samples, we can obtain the probability distribution

Table 1 Durations and Parameters of Each Construction Process

Unit: Day					
Process	Process number	Distribution	Optimistic duration (a)	Probable duration (m)	Pessimistic duration (b)
Erect 1# pier scaffold	1–2	Uniform distribution	1	2	3
Assemble 1# pier reinforcement	2–3	Triangle distribution	2	3	5
Do 1# pier body shuttering	3–5	Uniform distribution	1	1	1
Pour concrete into 1# pier body	5–7	Truncated normal distribution	1	2	3
Maintain 1# pier concrete before remove shuttering	7–9	β distribution	1	2	4
Remove 1# pier shuttering and maintain	9–11	Uniform distribution	1	1	1
Maintain 1# pier concrete after removing shuttering	11–14	β distribution	3	5	8
Erect 2# pier scaffold	2–4	Uniform distribution	1	2	3
Assemble 2# pier reinforcement	4–6	Triangle distribution	2	3	5
Do 2# pier body shuttering	6–8	Uniform distribution	1	1	1
Pour concrete into 2# pier body	8–10	Truncated normal distribution	1	2	3
Maintain 2# pier concrete before remove shuttering	10–12	β distribution	1	2	4
Remove 2# pier shuttering and maintain	12–13	Uniform distribution	1	1	1
Maintain 2# pier concrete after removing shuttering	13–14	β distribution	3	5	8

of the duration for 1# and 2# piers.

The frequencies which appear in repetitious simulations of the likely values of 1# and 2# piers construction durations are shown in Table 2 and Figure 6. In conclusion, the probability of the completion of the project in 23 days is 47.51%, and the probability of the completion of the project in 25 days is 89.13%, and the probability of the completion of the project in 27 days is 99.35%, which is close to 100%.

6 Conclusions

(1) This paper presents the Network Program Diagram and statistics-based simulation method of engineering total duration and expenses of a project. On the basis of the engineering practice, this method is available to determine the most probable value of construction duration and expenses.

(2) Analysis based on this field investigation has determined the mathematical distribution of resource consumption and duration of every process. The mathematical distribution of the parameters of each process has a great effect

on the results of construction duration and costs simulation.

(3) Based on BIM theory, it is possible to add the information related to project progress and project resources on physical model to create construction 4D modeling. This modeling can show the construction process of the real project virtually and resource consumption can be demonstrated visually at any time. Project managers can use this software to improve the construction progress and the efficiency of cost management.

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Table 2 The Statistical Table of 1# and 2# Piers Duration Simulation

Simulative duration(days)	Frequency of occurrence	Frequency	Accumulated frequency of occurrence	Accumulated frequency
18	5	0.0005	5	0.0005
19	15	0.0015	20	0.0020
20	171	0.0171	191	0.0191
21	620	0.0620	811	0.0811
22	1,513	0.1513	2,324	0.2324
23	2,427	0.2427	4,751	0.4751
24	2,464	0.2464	7,215	0.7215
25	1,698	0.1698	8,913	0.8913
26	752	0.0752	9,665	0.9665
27	270	0.0270	9,935	0.9935
28	60	0.0060	9,995	0.9995
29	3	0.0003	9,998	0.9998
30	2	0.0002	10,000	1.0000

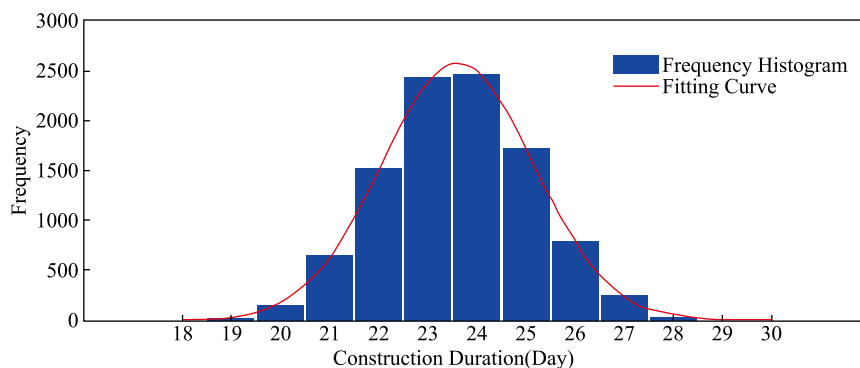


Figure 6. Frequency diagram of 1# and 2# piers construction duration simulation

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