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Estimating Project Completion Time with Monte Carlo Simulation

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Abstract: Risk and uncertainty are factors that construction project managers have been increasingly had to deal with. The expected project completion time is often shorter than the actual completion time. Monte Carlo simulation is a widely used simulation technique in modeling a process that is difficult to predict due to its random variables. This study provides a practical way to use Monte Carlo simulation to simulate a project completion time using functions available in a spreadsheet application. A project with five activities was simulated 2000 times using minimum, maximum, and expected duration. The mean, mode, and median simulation results were then plugged into their respective precedence diagram networks to compare them. The precedence diagram computations found that mean, mode, and median project completion times were longer than the initially expected completion time. The mean, mode, and median were 50, 53, and 48 days, respectively, which were 8, 11, and 6 days longer, respectively, than the 42 days initially expected. The study showed that the Monte Carlo simulation could assist the project manager in planning a project schedule that deals with risk and uncertainty more realistically.

Keywords: *Monte Carlo simulation, project scheduling, critical path method, precedence diagram method*

Abstrak: Risiko dan ketidakpastian adalah faktor-faktor yang semakin sering harus dihadapi oleh manajer-manajer proyek. Waktu penyelesaian yang diharapkan pada sebuah proyek sering kali lebih singkat daripada pada waktu penyelesaian yang sebenarnya. Simulasi Monte Carlo adalah sebuah metode simulasi yang umum digunakan dalam pemodelan sebuah proses yang sulit untuk diprediksi akibat adanya variabel-variabel acak di dalamnya. Studi ini menyediakan sebuah cara praktis dalam penggunaan simulasi Monte Carlo dalam menyimulasikan waktu penyelesaian sebuah proyek dengan menggunakan fungsi-fungsi yang terdapat pada sebuah aplikasi *spreadsheet*. Sebuah proyek dengan lima aktivitas disimulasikan sebanyak 2000 kali dengan menggunakan durasi minimum, durasi yang diharapkan, dan durasi maksimum. Nilai rata-rata, mode, dan median dari hasil simulasi digunakan sebagai durasi pada masing-masing diagram preseden untuk dibandingkan. Dari hasil perhitungan diagram preseden didapatkan bahwa nilai rata-rata, mode, dan median dari waktu penyelesaian proyek tersebut lebih lama daripada yang diharapkan sebelumnya. Nilai rata-rata, mode, dan median adalah masing-masing sebesar 50, 53, dan 48 hari yang masing-masing lebih besar 8, 11, dan 6 hari lebih lama daripada 42 hari, waktu penyelesaian proyek yang diharapkan sebelumnya. Studi ini menunjukkan bahwa simulasi Monte Carlo dapat membantu manajer proyek dalam merencanakan jadwal sebuah proyek yang mempertimbangkan risiko dan ketidakpastian secara lebih realistis.

Kata kunci: *simulasi Monte Carlo, penjadwalan proyek, metode jalur kritis, metode digram preseden*

1. Introduction

The construction industry has been extensively using the critical path method (CPM) to plan the construction schedule. CPM uses a single number to estimate each activity duration [1-3]. Hence it does not provide enough information on the uncertainty and risk associated with the activity durations [4].

Risks in construction projects are unavoidable [5-8]. Delay in project completion time is a risk that must be dealt with in construction projects. Many unanticipated reasons could hinder the project's completion on time [9]. It was estimated that around 80% of projects have high uncertainty at the start of construction [10]. Therefore, project managers begin acknowledging the importance of taking uncertainties into account when scheduling projects [9].

Monte Carlo simulation is one of the frequently employed methods in risk analysis [9], [11-15]. It is an analysis method where a computer model is iterated many times with the input variables (e.g., activity durations) chosen randomly for every iteration [16].

This study aims to provide a practical way to use the Monte Carlo simulation method in estimating a project duration using the Microsoft Excel spreadsheet application.

2. Material and Methods

2.1. Sample Application

A construction project consisting of five activities [17] was used as a sample application. The project's logical relationship between activities and their durations is shown in Table 1.

2.2. Network Analysis

The precedence diagram method [1-3]was used to draw and calculate the project network plan using the expected durations, as depicted in Figure 1. When the network was calculated with the expected activity durations, the project completion time was 42 days, and the critical activities were 1-4-5. The minimum activity durations yielded 37 days of the project completion time, and the critical activities were 1-4-5. The maximum activity durations resulted in 61 days of the project completion time, and critical activities were 2-3-4-5. Table 2 shows the results of the precedence diagram method calculations where the corresponding durations of the critical activities were written in bold with an asterisk to differentiate them from the non-critical activities.

Table 1. Logical relationship and duration, sdapted from [17]

No.	Activity	Immediately preceding activity	Duration in days		
			Minimum	Expected	Maximum
1.	Prefab Metal Building	-	20	22	25
2.	Clear Site	-	5	10	15
3.	Foundations	Clear Site	5	10	15
4.	Erect Building	Prefab Metal Building, Foundations	8	10	20
5.	Finish Building	Erect Building	9	10	11

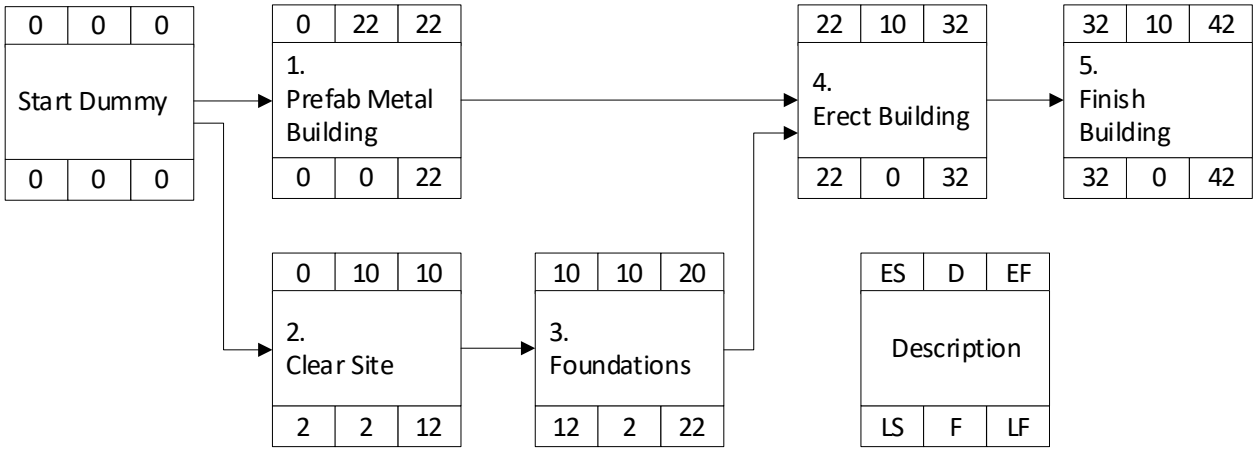

Figure 1. Precedence diagram calculation with the expected activity durations

Table 2. Precedence diagram calculation results

No.	Activity	Duration in days		
		Minimum	Expected	Maximum
1.	Prefab Metal Building	**20***	**22***	25
2.	Clear Site	5	10	**15***
3.	Foundations	5	10	**15***
4.	Erect Building	**8***	**10***	**20***
5.	Finish Building	**9***	**10***	**11***
The project completion time		37	42	61

* Critical activity.

2.2. Simulations

Monte Carlo simulation adheres to the following steps [18].

1) Create a quantitative model of $y=f(x_1, x_2, \ldots, x_n)$;
2) Generate random variables $x_1, x_2, \ldots, x_n$;
3) Evaluate the model and output stored in y_i;
4) Repeat steps 2 and 3 as needed (for i=1 to k);
5) Analyze the results

Monte Carlo simulation estimation on the activity durations was a random variable with a value between the minimum and the maximum duration. The multiplicative congruential method is the common mathematical method to obtain random numbers between 0 and 1 [19].

This study generated random numbers using a Microsoft Excel function called RAND. For example, the random duration of the prefab metal building activity in Table 2 was computed by =RAND()*(25-20)+20. This computation generated a random number between 20 and 25.

2.3. Number of Iterations

Total error in Monte Carlo simulation, which is proportional to the iteration number, can be calculated as follows:

$$\varepsilon = \frac{3\sigma}{\sqrt{N}} \quad (1)$$

where ε = total error; σ = standard deviation of random variable; N = number of iterations. Standard deviation was calculated based on the population, which in this case, consisted of only two members, namely the minimum and the maximum project completion time, which were 37 days and 61 days, respectively, as given by:

$$\sigma = \sqrt{\frac{\sum(x-\bar{x})^2}{n}} = 12 \quad (2)$$

where n = the number of populations; $\bar{x}$ = population average. If the absolute error of less than 2% is required, it is then calculated as follows:

$$\varepsilon = \frac{\bar{x}}{\left(\frac{1}{0.02}\right)} = 0.98 \quad (3)$$

The number iteration needed is given by:

$$N = \left(\frac{3\sigma}{\varepsilon}\right)^2 \approx 1350 \quad (4)$$

Hence, the number of iterations should equal to or greater than 1350. The number of iterations in this study was set to 2000. Each simulation result was rounded up to the

nearest whole number. For example, the simulated duration of 24.0959119 days was rounded to 25 days.

Unlike the project cost, which is simply the sum of all activity costs, the project completion time is not necessarily equal to the sum of all activity durations since the project completion time only considers the critical activity durations. This study only considers the three measures of the central tendency [20], [21], namely; mean, mode, and median durations of each activity based on 2000 iterations. The mean, mode, and median simulation results were then plugged into their respective precedence networks to obtain the project completion times.

3. Result and Discussion

3.1. Simulation Results

Monte Carlo simulation results of 2000 iterations are shown in Table 3. The precedence diagram calculation with each activity used the respective duration from the simulation's mean, mode, and median are shown in Figure 2, Figure 3, and Figure 4, respectively.

Table 3. Simulation results of 2000 iterations

No.	Activity	Simulation results in days		
		Mean	Mode	Median
1.	Prefab Metal Building	**24***	**25***	**23***
2.	Clear Site	11	8	10
3.	Foundations	11	11	11
4.	Erect Building	**15***	**17***	**14***
5.	Finish Building	**11***	**11***	**11***
The project completion time		50	53	48

* Critical activity.

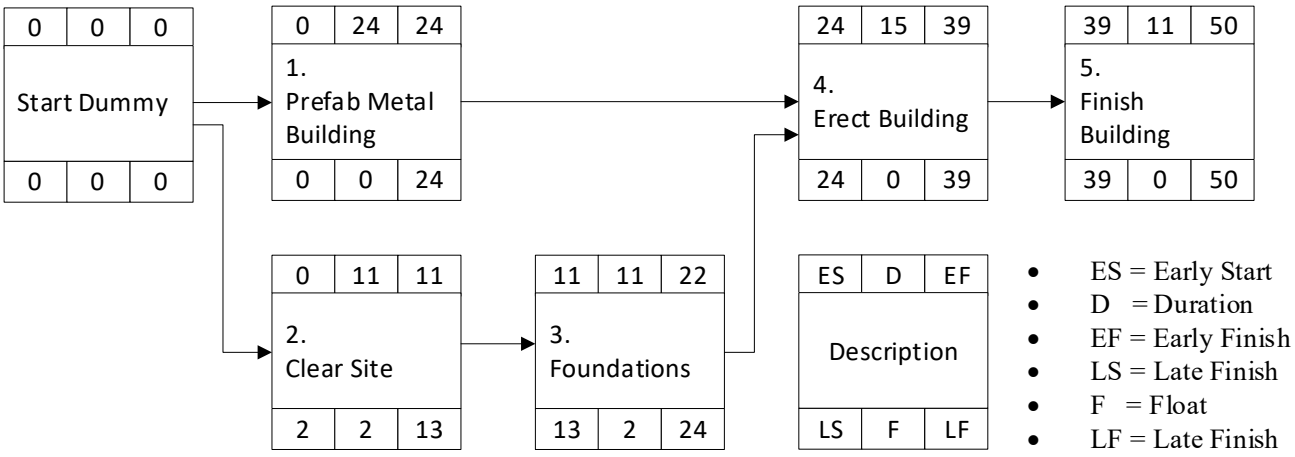

Figure 2. Precedence diagram calculation with the mean of simulated activity durations

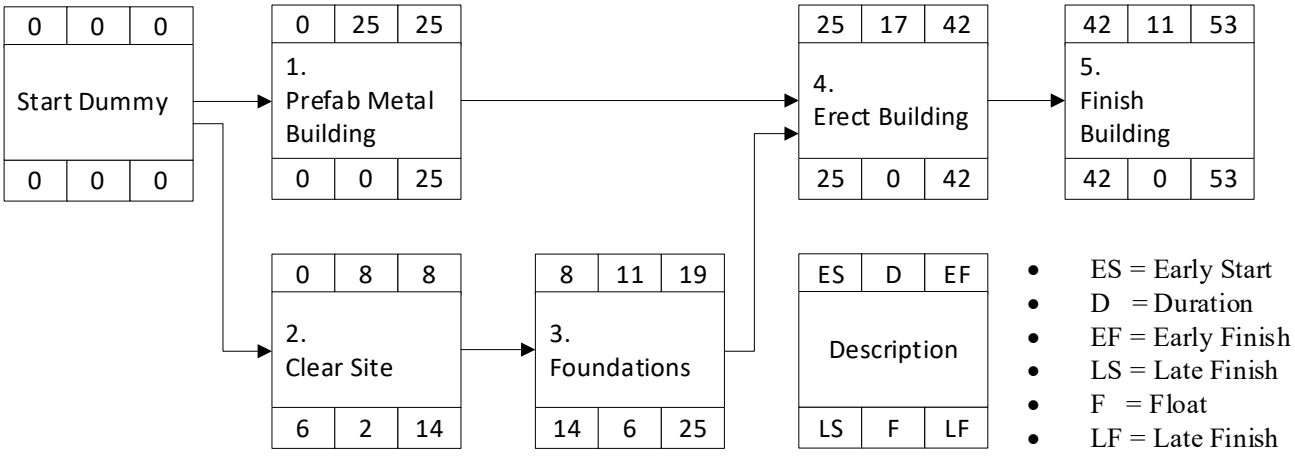

Figure 3. Precedence diagram calculation with the mode of simulated activity durations

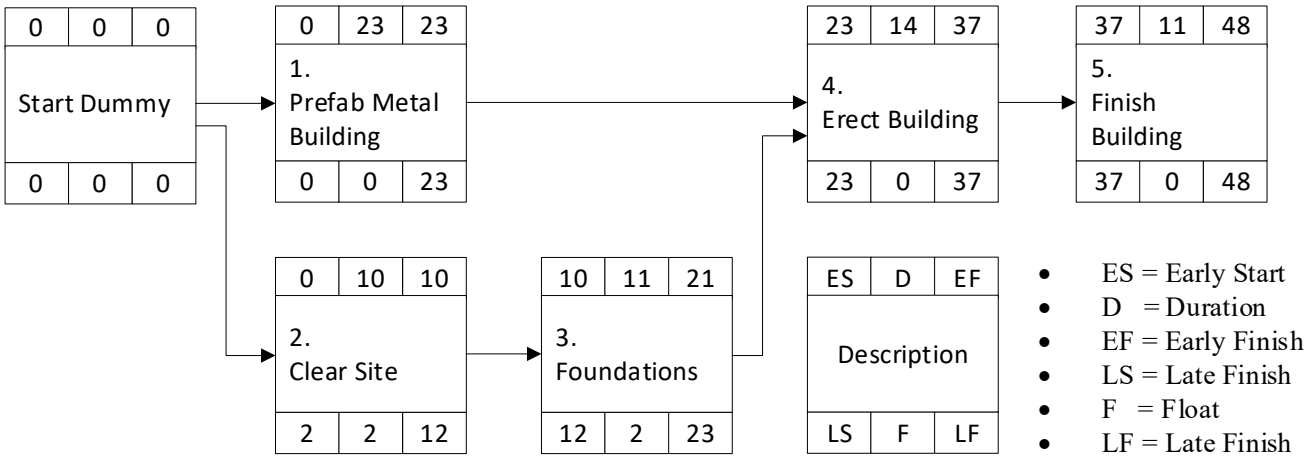

Figure 4. Precedence diagram calculation with the median of simulated activity durations

As shown in Table 3, the mean, mode, and median project completion times were 50, 53, and 48 days, respectively. None of the three measures of central tendency was shorter than or equal to the expected 42 days completion time.

The Monte Carlo simulation results predicted that the project would take longer than it was expected and showed that relying solely on the expected activity durations would not be enough to produce an adequate project schedule.

4. Conclusion

The results show that the Monte Carlo simulation can help the project manager plan a schedule considering risks and uncertainties. Even though Monte Carlo simulation is a powerful simulation method, as with other simulation methods, its results accuracy relies upon the input variables and the project model or network it simulates. If the project model is insufficient and the activity durations are inadequate, the simulation results will not be accurate.

It should also be noted that Monte Carlo simulation is not a solution provider. It only helps to predict a project's behavior that involves risks and uncertainties. It is the responsibility of the project manager to provide solutions by taking various aspects of the project into account.

If, for example, the project completion time cannot be postponed, the schedule could be compressed by fast tracking, crashing, or combining both methods to shorten the critical path. Doing so, however, will have consequences that must be thoroughly analyzed beforehand.

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