sustainability

MDPI

Article

Quantitative Analysis of Waiting Length and Waiting Time for Frame Construction Work Activities Using a Queue Model; Focusing on Korean Apartment Construction

Jin-Won Kim [1], Namhyuk Ham [2,*] and Jae-Jun Kim [1]

[1] Department of Architectural Engineering, Hanyang University, 222, Wangsimni-ro, Seongdong-gu, Seoul 04763, Korea; trustguys@gmail.com (J.-W.K.); jjkim@hanyang.ac.kr (J.-J.K.)
[2] Department of Digital Architecture and Urban Engineering, Hanyang Cyber University, 220, Wangsimni-ro, Seongdong-gu, Seoul 04763, Korea
* Correspondence: nhham@hycu.ac.kr; Tel.: +82-2-2290-0861

Abstract: The frame construction of an apartment complex that consists of multiple buildings encounters various uncertainties, owing to the complex relationships between units of work. Currently, the period of such a construction is calculated based on the number of floors of the highest building in the complex. This study quantitatively analyzes an apartment frame construction period using a queue model and evaluates the validity of the estimated period. In this regard, a methodology is proposed for analyzing the construction period by applying the concept of a customer and a server. A case study on the duration of an apartment frame construction period is conducted with the Korea Land and Housing Corporation, which has supplied the largest number of apartments in South Korea. It was found that the stable state of a queue system was observed when the rate of server utilization was applied to the basement and above-ground floors. However, a stable state was not reached on the ground floor. This study includes non-working days in its calculation and quantitatively analyzes uncertainty factors during construction. Therefore, the findings can be practically utilized to quantitatively plan the durations of work units in an apartment frame construction.

Keywords: frame construction; multiple buildings; construction period; uncertainty factors; queue model

check for updates

Citation: Kim, J.-W.; Ham, N.; Kim, J.-J. Quantitative Analysis of Waiting Length and Waiting Time for Frame Construction Work Activities Using a Queue Model; Focusing on Korean Apartment Construction. *Sustainability* **2021**, *13*, 3778. https://doi.org/10.3390/su13073778

Academic Editor: Víctor Yepes

Received: 9 March 2021
Accepted: 25 March 2021
Published: 29 March 2021

1. Introduction

Construction periods are generally determined during the planning stage to provide cost and schedule estimates [1]. Estimation accuracy is directly related to the success or failure of a project [2]. However, it is difficult to account for the uncertainty of construction, given that the work is incredibly complex and relies on dynamic environments [3]. Various work units, such as the installation of rebar, forms, electricity, communication systems, and concrete, can be conducted simultaneously in apartment complexes that consist of multiple buildings. For this reason, the lead–lag relationship between unit works is significantly complicated. Additionally, because the entirety of frame construction is performed outside, many more types of uncertainty exist because of weather. Construction methods, materials used, and human resources are volatile. Nevertheless, construction periods must be estimated based on units of work and planned resources [4]. Moreover, non-working days, which can occur due to worksite conditions, planned days off, and weather, must also be considered [5].

An apartment frame construction period is calculated based on a cycle per floor of the tallest building in the complex, regardless of project scale. However, this calculation method cannot properly reflect project scale, construction methods, work units, and human resources. Accordingly, delays are common, and they increase project cost and can result in a decrease in the quality of the finished work. Hence, anticipated rent income is delayed.

Existing estimation methods mainly apply probabilistic techniques to calculate an apartment frame construction period, which remains difficult because of the uncertainty factors [5–9]. These methods increase estimation accuracy to a certain extent, but they are unlikely to be practically applied, owing to the difficulty in verifying ground truth estimations [10].

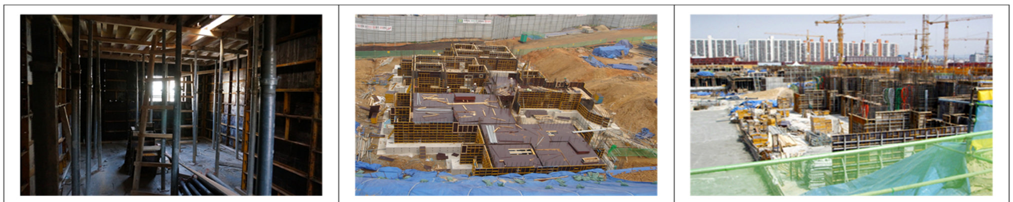
This study quantitatively analyzes an apartment frame construction period that is regarded as being multi-project type. It reviews the validity of the period based on the tallest building in the complex. Notably, methods and resources vary according to construction sections. In this regard, floors are classified as basement, ground, and typical (i.e., second and above) for analysis. Furthermore, the duration of construction sections is quantitatively examined in consideration of the work units and resources required. Doing so, this study optimizes the apartment frame construction period estimation method to better support project planning.

2. Literature Review

2.1. Characteristics of Apartment Frame Construction

Korean housing types are divided into apartments, detached houses, row houses, multi-family houses, and houses in commercial buildings. Apartments are the representative type of housing in Korea, accounting for 62.3% of all housing units as of 2019 [11]. About 600,000 apartments have been supplied to Korea over the past seven years. Korea Land and Housing Corporation (LH), Korea's representative public institution for housing supply, supplied approximately 68.5% of the total supply [12]. Frame construction of these apartment construction works is carried out from the outside, and various unit works are carried out simultaneously. Therefore, various uncertainty factors that may occur during the construction phase can directly affect the construction period.

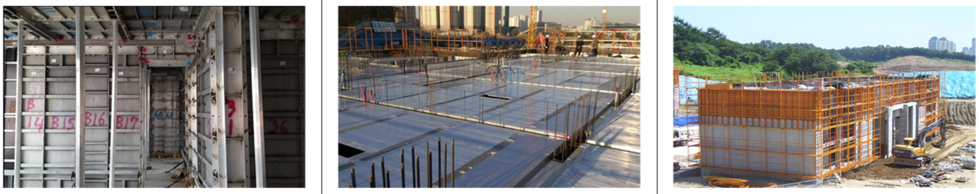
Frame construction comprises unit works of marking, rebar assembly, forms, slabs, electrical wiring, communication plants, machinery, and concrete. Form assembly accounts for the highest proportion of apartment frame construction and requires a variety of materials and construction methods according to the planned sections, as shown in Figure 1.



(a) Walls for the basement level (Euroform)

(b) Slabs for the basement level (plywood)

(c) Outer walls for the basement level (Euroform)



(d) Walls for the ground level (aluminum form)

(e) Slabs for the ground level (aluminum form)

(f) Outer walls for the ground level (gang form)

Figure 1. Types of formwork according to floors in apartment frame construction.

A conventional construction method uses Euroform and plywood in the basement floor of an apartment, and a system construction method based on gang and aluminum forms is applied to the ground floor [13]. After setting these forms on the ground floor, the same work is repeated upward per floor. Thus, the cycle per floor is significantly shorter for the ground floor than for the basement.

A typical floor construction plan is established mainly based on formwork, which accounts for a large proportion of the entire project, as shown in Figure 2. The cycle per floor is generally 8 days. However, based on working days vs. non-working days, 10 to

12 days are generally required [14]. Hence, the formwork crew is generally tasked with three buildings simultaneously to minimize idle time and to facilitate efficiency. Therefore, the construction period for apartments consisting of two or more buildings should be calculated in consideration of lead–lag relationships between work units, the number of actual working days, the number of non-working days, resource allocation, and idle time.

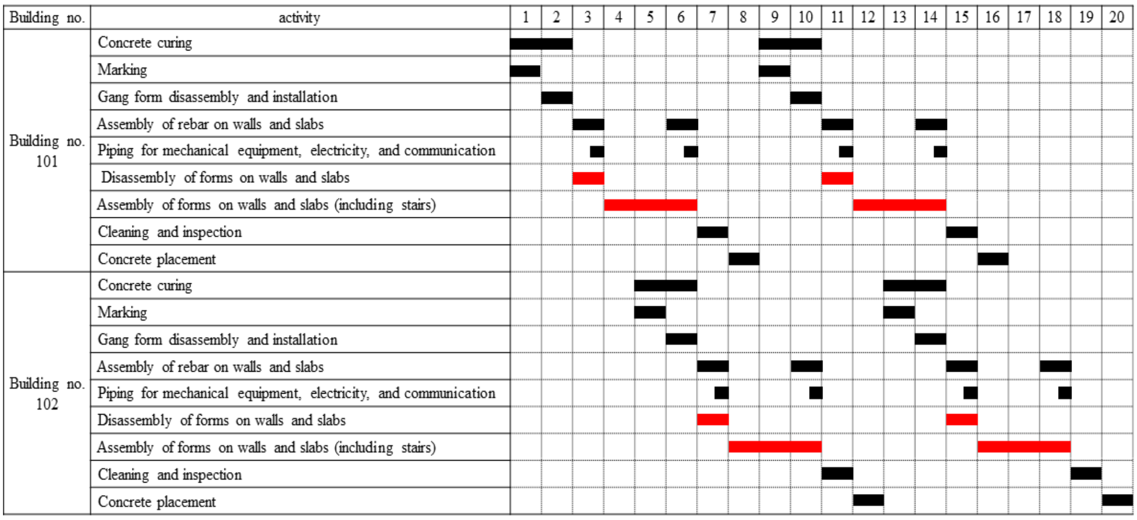


Figure 2. Construction planning for a typical floor in apartment frame construction.

2.2. Uncertainty Factors in Apartment Frame Construction

Generally, factors affecting a construction period include design, labor, materials, equipment, subcontracts, weather, planning, and execution [15]. These factors can cause delays and interruptions owing to the mentioned uncertainties [16]. McTague and Jergeas [17] reported that 35% of the entire work time was wasted because of delays, and that preparation time accounted for 28% of the work time. This implies that actual working time occupies only 50% of the entire work period. Formwork accounts for the other half [18]. Thus, optimization should account for both.

Studies conducted on the calculation of the construction period of apartment frame construction provided an appropriate construction period based on the general design conditions and cycles per floor [19,20] or developed a model to calculate the probabilistic construction period using weather information and holidays [14,21,22]. Altuwaim [23] developed a model to shorten the construction period of repeated projects and minimize disruption, while EL-Abbasy [24] developed an automation system to optimize the schedule of construction projects by utilizing genetic algorithms to simultaneously manage multiple projects. However, these studies have limitations in reflecting various uncertainty factors that may occur in the construction phase of the project in the construction period.

2.3. Research Methods for Quantifying Uncertainty

Most apartment frame constructions apply repeated and sequential methods. When a certain work is delayed, adjacent work is also delayed until the previous work is finished. This phenomenon is exacerbated for framing jobs, which occur outdoors. Past studies optimized apartment frame construction period estimation by focusing on the uncertainty factors. Specifically, probabilistic methods were used to apply weather factors [5,6] and human resources [7], relying on support vector machine (SVM) algorithms and artificial neural networks (ANNs) [8,9].

Jung [5] developed a model that estimates high-rise building construction delays according to weather conditions (e.g., temperature, wind velocity, and precipitation). Lee [6] presented a model that could estimate construction periods based on the number of floors in the frame construction, alongside regional climate conditions and expert opinions.

These methods could unfortunately only be applied to projects in which the same works were consecutively repeated (e.g., roads and typical framed floors).

Leu [7] proposed a model for integrating the concepts of time–cost trade-offs and resource allocation, and developed a method for optimizing resource elements during process planning. However, this method could only be used for construction works that applied a line-of-balance technique. This technique is unlikely to be used in multi-projects such as apartment frame construction.

Petruseva et al. [8] proposed an SVM-based learning algorithm trained with the contract and price data of 75 projects to increase estimation accuracy. Golizadeh et al. [9] presented an ANN model that estimated a construction period that considered the structural elements of frame construction. Although these methods quantitatively estimated construction periods using machine-learning techniques, they were limited in that specific processes for deriving analytic results could not be precisely verified (i.e., the ground truth problem).

Therefore, workflow management (WFM) techniques, which account for lead time, wait time, service time, and resource utilization [25], have been used. A queueing theory is generally applied to analyze performance, because it is suited to the mathematical processes required. Moreover, it can be utilized to effectively examine the network workflow of various activities [26].

Queueing theory was developed to support examinations of various waiting cases that can be practically observed. Figure 3 diagrams this model.

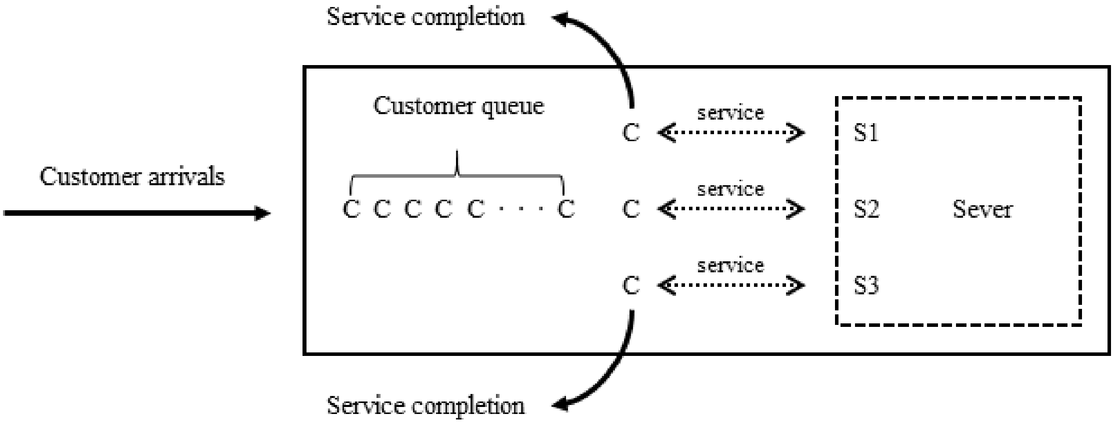


Figure 3. The queue system.

This theory can be used to quantitatively analyze the appropriate scale of a service facility based on probabilities related to customer arrival time, service time, and idle time. Customers individually enter a queueing system to receive a service, and a queue occurs when a customer who reaches the queue system waits without receiving a service. Generally, more than one single server provides services to customer, and the customer leaves the queue system after service is completed. Eventually, the queue is eliminated. This queue model can be applied in both daily life and various professional fields, such as computer programming, networking, medicine, and banking [27].

Civelek [28] studied the impact of bivariate and temporal dependencies among interarrival and service times on the performance of single-server queues. Siddiqui [29] proposed an QPSL queue model for load balancing in cloud computing. In the construction field, a related study was conducted to apply the concept of customer–server queuing with regard to construction equipment for concrete placement and excavation [30]. Additionally, Ham [31] presented a framework for quantifying the impact of Build Information Modeling (BIM) staffing.

3. Research Method

As noted, work units per floor based on their lead–lag relationships are repeated for apartment frame construction. Thus, wasted time must be quantitatively analyzed to optimize period estimations. A queue model can quantitatively analyze waiting times for customers waiting for a service. This study applies the concept of customer–server queue relationships in estimating apartment frame construction.

3.1. Definition of Customer and Server

Table 1 lists the details of the queue model established to quantitatively analyze an apartment frame construction period according to construction sections. In this model, floors are classified as basement, ground, and typical (i.e., second and higher) according to the construction methods applied to each type of formwork. A customer is a work unit per construction section, and a server reflects the work crew performing the unit of work. As the customer and the server are determined based on the amount of work and the number of teams, productivity data related to a target work unit can be utilized to estimate the apartment frame construction period. Moreover, a construction period for the target work unit can be shortened via the adjustment of the number of teams (servers). Works for the basement floor are classified as rebar works and formworks, which account for half of the entire work. Works for the ground floor are classified as gang- and aluminum-form setting. On a typical floor, the same works are repeated. Thus, all work units performed for concrete placement on each floor are considered.

Table 1. Establishment of the queue model.

Floor	Form Method	Customer (Work Quantity)	Server (Working Group)	Code
basement	Euroform & plywood	area of the form work	carpenter	Ba
		weight of rebar	rebar worker	Bb
ground	gang form & aluminum form	area of the form work	gang form worker	Ga
		length of gang form	carpenter	Gb
typical		duration of concrete pouring per floor	carpenter	Ta

3.2. Establishment of a Basic Performance Scale

In the queue system, inter-arrival times account for the time between the arrival of a customer and that of another. When arrival data are sufficiently collected, the average number of customers per unit time can be estimated, giving the mean arrival rate, λ. As the time when customers reach the queue is irregular and varies depending on conditions, the probability distribution for inter-arrival times in most models take on an exponential distribution. Thus, an estimated mean inter-arrival time for queue is defined as $1/\lambda$.

Service time in the queue system refers to the time from which a customer begins receiving the service until the service is completed. Assuming that a server works without a break, the mean service rate is the average number of customers who receive completed services from the server per unit time, μ. Generally, service time differs according to service types requested. Thus, the probability distribution takes the form of an exponential distribution, and the estimated mean service time is $1/\mu$.

Performance criteria for the queue system can be derived based on the mean arrival rate, the mean service rate, and the server, as shown in Figure 4. Performance criteria are classified using the following four criteria according to whether only customers waiting for the queue system are considered, or whether a customer receiving services in the queue system is also considered.

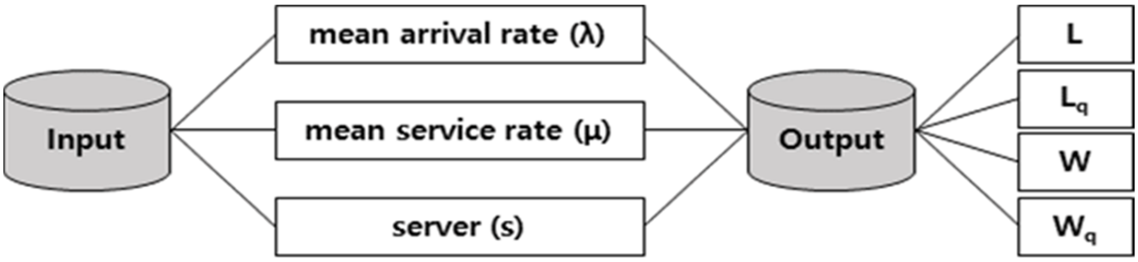


Figure 4. Input and output variables of the queue model.

In Figure 4, L is the mean number of customers being accessed in the queue system, including any customer receiving a service. Lq is the mean number of customers waiting in a queue, with the exception of any receiving a service. W is the mean waiting time of each customer in the queue, including service time. Wq is the mean waiting time of each customer in the queue, excluding service time.

3.3. *Performance-Scale Analysis Method*

An analysis of performance criteria for the queue system requires basic information on the amount of work being performed according to construction sections, an estimated construction period, a practical construction period, and the number of work crew. Based on such information, input variables of the queue model, such as mean arrival rate (λ), mean service rate (μ), and server (s), can be identified. Equations are defined as follows:

$$\lambda = \frac{(\text{entire amount of work for a customer (unit work)}}{(\text{estimated construction period for a service (work)}} \tag{1}$$

$$\mu = \frac{(\text{entire amount of work for a customer (unit work)}}{(\text{practical construction period for a service (work)}} \tag{2}$$

$$\text{s} = (\text{number of work group input according to unit works}) \tag{3}$$

Little's formula is applied to identify basic performance criteria for the queue model [32], and the relationship between L and W is defined with Equation 4. This equation can also be applied to the relationship between Lq and Wq. When one of L, Lq, W, or Wq is analyzed, the other performance criteria can be easily calculated. Those that can be used to analyze a fundamental state of a service are determined through the following equation.

Other than basic performance criteria, the probability related to a state of the queue system, such as the number of customers being accessed in the queue system and waiting time, can also be analyzed. When the rate (ρ) of server utilization is high, the state of the queue system becomes worse. When waiting time increases, the point of server input that provides the service can become delayed. Thus, the appropriate scale of the servers can be determined via the probabilistic analysis of time in the queue system to optimize an apartment frame construction period.

$$\text{L} = \lambda\text{W} \tag{4}$$

$$\text{P}_0 = \frac{1}{\sum_{\text{n}=0}^{\text{s}-1}\left(\frac{\left(\frac{\lambda}{\mu}\right)^{\text{n}}}{\text{n!}}\right) + \frac{\left(\frac{\lambda}{\mu}\right)^{\text{s}}}{\text{s!}}\left(\frac{1}{1-\frac{\lambda}{\text{s}\mu}}\right)} \tag{5}$$

$$L_q = \frac{P_0\left(\frac{\lambda}{\mu}\right)^S \rho}{s!(1-\rho)^2} = \frac{P_{0\lambda}{}^{s+1}}{(s-1)!\mu^{s-1}(s\mu-\lambda)^2} \tag{6}$$

$$\text{W}_\text{q} = \text{L}_\text{q}/\lambda \tag{7}$$

$$\text{W} = \text{W}_\text{a} + \frac{1}{\mu} \tag{8}$$

4. Case Study

Figure 5 shows an Excel-based construction period estimation tool, which has been applied to apartment construction projects ordered by LH. This tool can be used easily because it calculates the construction period from basic project information (e.g., region, dates, households affected, and number of floors). However, it exhibits limited performance regarding the uncertainty that can occur during construction, given that it calculates the period based on the number of floors of the highest building, regardless of the project scale, as shown in Figure 6. Thus, the construction period according to construction sections and the entire amount of work was quantitatively analyzed based on the performance data of apartment frame construction projects ordered by LH.

공사명: oo지역 아파트 건설공사 1공구

(a) Basic conditions

분류		구분	선택사항	비고
1. 기본사항		가. 주택유형	공공분양	
		나. 세대수	850세대	
		다. 지역	수원(화성, 오산, 의왕, 안양, 군포, 과천)	
		라. 최고층수	20층	
		마. 착공일	2018-06-01	
		바. 골조방식	일반 건축공사	
2. 보정	가. 지하층	지하주차장	주동통합(1개층, 150대이상)_14일	
	나. 지상층	1) 거푸집	시스템 거푸집	
		2) 조립식욕실	X	
		3) 단차	X	
		4) 지붕	해당없음	
	다. 기타	1) 지역	해당없음	
		2) 조경공사	제외	
	라. 추가	항목	일수	

분류	항목	시작일	종료일	일수
3. 기타	공사지연기간1	2018-07-01	2018-09-30	92
	공사지연기간2			
4. 참고사항	골조공사 가열보온 양생기간 (2급지 - 12.1~2.28)			
	마감공사 불능기간 (2급지 - 12.13~2.25)			
5. 기타 공사여건				

(b) Specific construction condition input parts

구 분			산정기준	산정일	비고
토목 공사	토공사 (터파기)		토목 토공사 : 현장여건에 따라 산정	20	
			지하층 1개층 : 8일	8	토목터파기 8일
			지하층 1개층 초과 : 10일 추가		초과하는 매층마다 (토목터파기)
			지하층 4.5M 초과 : 10일 추가	10	
			암반,전석이 있는경우 : 현장여건에 따라 추가		
	흙막이		자립식 10일, E/A식 20일	10	L=120M, H=7M
건축 공사	터파기		지하층 1개층 : 2일	2	건축터파기 2일
	기초 공사	파일 기초	15m이하 : 24일		파일 혼합시 혼합비율에 따라 산정
			16m~30m이하 : 44일		
			30m초과 : 별도산정		
			15m이하 선굴착 : 40일	40	
			16m~30m이하 선굴착 : 80일		
			선굴착공법 지지력시험 : 11일	11	
			파일량 3,000본 이상 : 5일		
		부상방지	지하주차장 부상방지 어스앵커 10일		
		내림기초	내림기초 3m : 15일, 6m : 30일, 9m : 45일		
	골조 공사	지하층	1개층 31일, 2개층 51일	31	
			2개층 초과시 초과하는 매층마다 21일		
		지상층	층고차이에 따른 추가 반영일수		

(c) Notification

- 나주의 경우 비작업일수는 3급지(광주광역시), 동절기 기간은 4급지 적용됨.
- 공사준비기간 30일 포함(토목공사기간에 반영).

(d) Construction period estimation results

구분	날짜	비고
착공일	2018-06-01	
토목공사 착공일	2018-06-01	
건축공사 착공일	2018-11-18	
지상1층 완료일	2019-04-16	비작업일 포함
건축공사 완료일	2020-09-07	
토목공사 완료일	2020-09-22	

총공사기간	2018-06-01 ~ 2020-09-22
건축 공사기간	2018-11-18 ~ 2020-09-07
총공사(순공사) 일수	845 (683)
건축공사 일수	660 (비작업일 : 200) 동절기 층수 : 2개층(2층이상)
토목공사 일수	155 (비작업일 : 16)
조경공사 일수	제외

(e) Bar chart of construction period based on calendar days

착공일	준비기간	토목공사	가산	건축터파기 및 기초공사	가산	지하층 골조	지상층 골조 (보정포함)	마감공사 (동절기 및 보정 포함)	마감동절기	마감공사 동절기 보정	토목공사	조경공사
2018-06-01	2018-06-30	2018-11-17	2018-11-17	2019-01-09	2019-01-10	2019-03-22	2019-12-17	2020-09-07	70일	0일	2020-09-22	제외

(a) Basic conditions : housing type, number of households, region, highest number of floors, date of commencement of construction, framework type, the basement floor, basement garage, ground floor, forms, height difference, roofs, other construction conditions
(b) Specific construction condition input parts : standard for calculating the construction period considering the design conditions of civil engineering and building works
(c) Notification : special notices and announcements of the project
(d) Construction period estimation results : date of commencement of engineering work, date of completion of ground floor construction, date of completion of building construction, date of completion of engineering construction, the entire construction period, number of the entire (net) construction days, number of days for building construction, number of days for engineering construction, number of days for landscape construction
(e) Bar chart of construction period based on calendar days : the construction period for each stage of construction is displayed based on the date of the calendar

Figure 5. Construction period calculation tool used by LH.

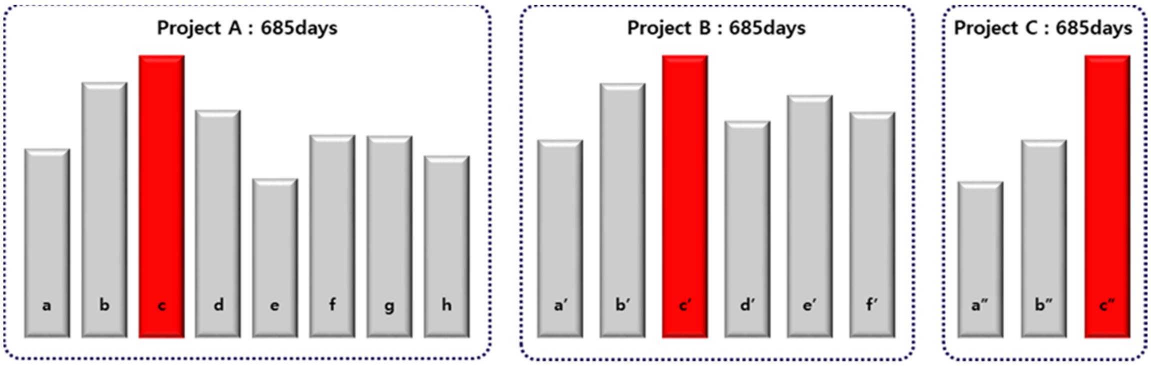


Figure 6. Examples of construction period calculation results for projects ordered by LH.

4.1. Overview of a Construction Period

Table 2 indicates details of the most common project types executed by LH, which are comprised of eight apartment buildings of 450 households with areas of exclusive use of 59 or 84 m^2. The entire construction period for this project was planned for 846 days, and the apartment frame construction period was planned for 336, based on the number of floors in the highest building (19), and non-working days were considered. The construction periods for the basement floor, the ground floor, and the typical floor were planned to take 84, 26, and 226 days (12.5 days per floor), respectively.

Table 2. Overview of construction for a project selected as an analysis target in this study.

Classification	Overview
Location	Geumgok-dong, Gwonseon-gu, Suwon-si, Gyeonggi-do
Construction period	846 days (336 days for frame construction)
Construction cost	44,996,785,000 won (KRW)
Site area	27,804 m^2
Gross floor area	65,678 m^2
Number of buildings	8
Highest number of floors	19
Number of households	450
Supply type	sale
Building to land ratio	20.42%
Floor area ratio	169.88%

4.2. Data Collection and Classification

Table 3 displays the data of planned processing tables, concrete placement management reports, work histories, and interview results, which were used for analysis. The amount of work is the sum of work units per floor, and the work proportion is the ratio of a work unit according to construction sections based on the entire amount of work. A construction period estimation tool developed by LH was used to calculate the estimated frame construction period. Construction periods per floor were multiplied with the work proportions of each work unit to calculate estimated construction periods according to the construction sections. Regarding the practical frame construction period, that of concrete placement management reports was analyzed and multiplied with the work proportion. Information on daily productivity and work crew formation was obtained from interviews with a responsible LH worker.

Table 3. Data collection and classification.

Floor	Code	Amount of Work	Work Proportion	Duration (Days)		Daily Productivity
				Estimated	Executed	
basement	Ba	12,821 m^2	0.48	40.65	66.29	12.39 m^2/man-day
	Bb	325 ton	0.29	24.39	39.77	1.22 ton/man-day
ground	Ga	11,738 m^2	0.33	8.67	33.00	22.96 m^2/man-day
	Gb	1101 m	0.28	7.22	27.50	27.52 m/team-day
typical	Ta	120 F	1.00	226	266	0.45 f/day

Table 4 shows the results of the apartment frame construction performance analysis based on unit works in consideration of the construction periods. Ratios ($\rho = \lambda/s\mu$) of server utilization on the basement and typical floors satisfy the condition ($\rho < 1$), where a queue can reach a stable state. However, the ρ value for the basement floor was calculated to be 0.82, indicating that the server was fairly busy. In other words, when an uncertainty factor occurs during a construction stage, it can create a significant delay for the entire job.

The ratio of server utilization on the ground floor was calculated as 1.27, which failed to satisfy the condition of queue stability. The ratio of server utilization on a typical floor was calculated to be 0.39. It was analyzed that the server stayed fairly stable because 61% can participate in works other than the typical floor.

Table 4. Performance analysis indices for apartment frame construction periods.

Code	Mean Arrival Rate (λ)	Mean Service Rate (μ)	Number of Server (s) (man/s)	Server Utilization ($\rho = \lambda/s\mu$)	Server Efficiency (1-ρ)
Ba	152.63	93.59	2 (13/1)	0.82	0.18
Bb	13.33	8.17	2 (12/1)		
Ga	1354.39	355.70	3 (15/1)	1.27	-
Gb	152.45	40.04	3 (5/1)		
Ta	0.53	0.45	3 (15/1)	0.39	0.61

4.3. Construction Period Analysis According to Concrete Placement Days

Figure 7 shows the result of apartment construction periods per floor based on concrete placement days.

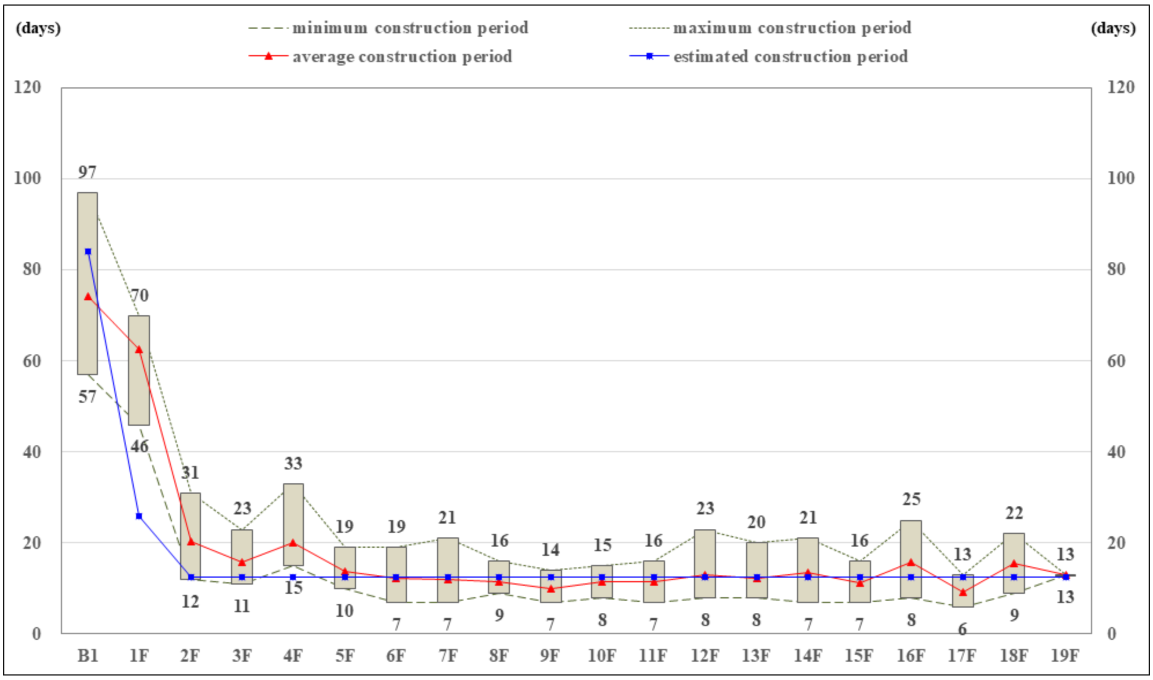


Figure 7. Analysis results of construction periods based on concrete placement reports.

Specifically, this result was examined according to the minimum construction period, the maximum construction period, the mean construction period, and the estimated construction period. The estimated apartment frame construction period per floor is generally located between the minimum and maximum frame construction periods. However, the estimated construction period for the ground floor, which was calculated as 26 days, was significantly lower than the executed construction period (46 days minimum and 70 days maximum). Moreover, when comparing the minimum construction period and maximum construction period for each floor of the eight buildings, the deviation in the construction period for each floor of the framework was analyzed to be 40 days for the basement, 24 days for the first floor, and 29 days for the second floor.

This result verifies that idle time occurred, owing to various uncertainty factors during the initial construction stage. It was analyzed that such phenomena occurred because of the following reason: in apartment frame construction, a work crew team is responsible for two or more buildings; thus, they sequentially perform the work. Consequently, waiting time is generated dependent on the on-site conditions, leading to delays in the construction period.

In fact, the mean construction period for the basement floor in eight buildings was shorter than the estimated construction period. On the other hand, the completion point of the entire work for the basement floor was delayed by 137 days compared with the estimated completion point. Furthermore, the completion point of the entire work for the ground floor, characterized by the setting of aluminum and gang forms, was also delayed by 99 days compared with the estimated end point. Based on this, it can be shown that an estimated apartment construction period, which is calculated based on the number of floors of the highest building selected through a critical-path analysis, is merely a guideline for project ordering. In other words, this estimated period cannot be effectively used to organize work crews or establish process plans. Therefore, the conditions of a target project, such as the entire amount of work, resource inputs, and productivity, should be comprehensively considered to optimize apartment frame construction period estimation.

4.4. Construction Period Analysis Based on a Queue Model

Table 5 shows the result of the analysis of the waiting length and the waiting time during apartment frame construction periods according to floors based on performance analysis indices. The mean arrival rate and the mean service rate for apartment frame construction were calculated based on construction periods according to floors and the number of working teams according to work units. For this reason, waiting length was calculated to be consistent for all floors. Thus, L and Lq, consistent to waiting length, were converted into work amounts (e.g., m^2/days, ton/days, and floor/days) via the multiplication of the number of work crews for a corresponding work unit and daily productivity. W and Wq, consistent with waiting time, were converted into time (h) through multiplication by 9 h, the mean working time per day in apartment frame construction.

Table 5. Analysis results of basic performance criteria on the construction periods per floor.

	Analysis Results				**Unit Conversion**			
	L	**Lq**	**W**	**Wq**	**L**	**Lq**	**W**	**Wq**
Ba (s = 2)	4.87	3.24	0.03	0.02	784 m^2	521 m^2	0.3 h	0.2 h
Bb (s = 2)	4.87	3.24	0.36	0.24	75 ton	50 ton	3.2 h	2.2 h
Ga (s = 3)	-	-	-	-	-	-	-	-
Gb (s = 3)	-	-	-	-	-	-	-	-
Ta (s = 3)	1.26	0.88	2.38	0.16	8.5 f	5.9 f	1.4 h	0.4 h

L, Lq, W, and Wq for the formwork (Ba) on the basement floor were calculated to be 784 m^2, 521 m^2, 0.3 h, and 0.2 h, respectively. L, Lq, W, and Wq for rebar work (Bb) were calculated to be 75 tons, 50 tons, 3.2 h, and 2.2 h, respectively. A ratio (ρ) of server utilization for frame construction on the basement floor was calculated to be 0.82, indicating that the server was fairly busy and that a queue requiring ~3 h was needed for rebar work (Bb). As a queue is unlikely to occur in a system for formwork (Ba) on the basement floor, it can exert significant effects on the execution point of the follow-up rebar work (Bb). Therefore, it was analyzed that schedule management for formwork should be performed to prevent any delays on the basement floor.

A ratio of server utilization on the ground floor was calculated to be 1.27, which failed to satisfy the condition ($\rho < 1$), where a queue can reach a stable state. This phenomenon occurred because of the following reasons: first, a construction period for the ground floor was estimated to be 26 days, whereas it was practically delayed to be 99. Moreover, various uncertainty factors that might occur during a construction stage were not reflected in the process of estimating an apartment frame construction period. Based on this, it can be concluded that the period required for setting a gang form and an aluminum form should be sufficiently reflected to optimize the construction period for the ground floor.

L, Lq, W, and Wq for work (Ta) based on a cycle on a typical floor were calculated to be 8.5 f, 5.9 f, 1.4 h, and 0.4 h, respectively, indicating that waiting durations were partially generated. However, because the ρ value was calculated to be 0.39, it was analyzed that the server was in a fairly stable state. This phenomenon was observed because delayed construction periods for the basement floor and the ground floor also led to a delay in the execution of work on a typical floor. Therefore, it was evaluated that the estimated construction period for the typical floor was appropriately calculated.

When the analysis results are summarized, it can be seen that the uncertainty factors of the frame construction occur more in the basement and the first floor than in the typical floor, and that the formwork that generates atmosphere has a direct influence on the construction period. In addition, since the planned construction period of the first floor is very different from the actual construction period, it is judged that the method of calculating the construction period needs to be improved. The results of this study can quantitatively predict the waiting length and waiting time for each construction part of the frame construction, so that the process plan can be established efficiently and can be used for the proper arrangement of human resources according to the size of the project.

5. Discussion

This study examined the differences between an estimated frame construction period for an apartment complex consisting of multiple buildings and its practical period to determine the degree of accuracy using a quantitative analysis. Existing studies [5,6] on analyzing apartment frame construction periods adopted probabilistic methods to solve issues related to uncertainty. This study is different from those in that it quantitatively analyzed an estimated construction period reflecting not only weather conditions but also non-working days and idle time. Moreover, it inspected the validity of an estimated construction period according to construction sections by classifying an analysis range for the construction period using basement, ground, and typical (i.e., second and above) floors in consideration of the applied construction methods, materials, and work crew formation. Additionally, this study quantitatively analyzed waiting durations according to construction sections through the application of a queue model, which can be further utilized to effectively distribute resources in consideration of the scale of the apartment frame construction. The most common project executed by LH, which has supplied the largest number of apartments in South Korea, was selected as a case study. Representativeness of samples is suspect, given that the construction period analysis was performed based on only a single project. However, the practical construction period for the ground floor analyzed in this study was delayed by ~350% over the estimation. Since the method of calculating the construction period of the ground floor is not related to the size of the project, similar results are expected for other projects.

Based on the results of this study, it can be shown that an estimated construction period for the ground floor should be adjusted through sufficient consideration of the period required for on-site delivery of gang- and aluminum-form materials, material inspections, settings, and quality confirmations. Furthermore, this study is significant in that its findings can be used to practically evaluate the validity of construction periods to further optimize estimated construction periods via constant feedback.

6. Conclusions

The frame construction period for apartments being built in South Korea was determined based on the number of floors in the highest building in a target apartment complex, regardless of the scale or the entire scope of work. Various uncertainty factors that can occur during a construction stage can cause delays and force consecutive work to be rescheduled. Due to these and other uncertainty factors, unnecessary idle time is generated during construction. This study, in turn, quantitatively analyzed a practical construction period using a case study to examine how accurately an apartment frame construction period was estimated. The analysis range for apartment frame construction was classified as basement, ground, and typical (i.e., second and above) floors in consideration of the applied construction methods, materials used, and the number of work crew inputs. A queue model was utilized to calculate performance criteria related to waiting durations. Performance data on estimated and practical construction periods, work crews according to unit works, and daily productivity were collected and used for analysis.

This study is distinguished from extant ones in that it evaluated the validity of a construction period according to construction sections using a quantitative analysis, unlike the other studies that estimated periods based on only empirical data and monitoring results. Furthermore, the results of this study can be used to develop guidelines for establishing process planning, because waiting length and waiting time according to unit works in apartment frame construction can be quantitatively identified from a practical perspective. Additionally, the concept of a customer–server relationship, which is derived from queueing theory, applies to the analysis of construction periods for various projects, given that relevant data can be easily collected. Additionally, the method proposed in this study can be applied not only to apartment construction but also to all construction works such as excavation work, foundation work, and interior work.

Nevertheless, this study has a limitation in that a practical apartment frame construction period was analyzed based on only a single project. Thus, further research is needed to quantitatively analyze practical construction durations and to optimize the queueing model.

Author Contributions: Conceptualization, J.-W.K. and N.H.; methodology, J.-W.K. and N.H.; validation, J.-W.K.; formal analysis, J.-W.K. and N.H.; investigation, J.-W.K.; data curation, J.-W.K.; writing—original draft preparation, J.-W.K.; writing—review and editing, N.H. and J.-J.K.; visualization, J.-W.K.; supervision, J.-J.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The data presented in this study are not publicly available due to the continuation of research. The data are available on request from the corresponding author.

Conflicts of Interest: The authors declare that there are no conflicts of interest.

References

1. Sonmez, R. Conceptual cost estimation of building projects with regression analysis and neural networks. *Can. J. Civ. Eng.* **2004**, *31*, 677–683. [CrossRef]
2. Bayram, S. Duration prediction models for construction projects: In terms of cost or physical characteristics? *KSCE J. Civ. Eng.* **2017**, *21*, 2049–2060. [CrossRef]
3. Mulholland, B.; Christian, J. Risk assessment in construction schedules. *J. Constr. Eng. Manag.* **1999**, *125*, 8–15. [CrossRef]
4. Lu, M.; Li, H. Resource-activity critical-path method for construction planning. *J. Constr. Eng. Manag.* **2003**, *129*, 412–420. [CrossRef]
5. Jung, M.-H.; Park, M.-S.; Lee, H.-S.; Kim, H.-S. Weather-delay simulation model based on vertical weather profile for high-rise building construction. *J. Constr. Eng. Manag.* **2016**, *142*, 04016007. [CrossRef]
6. Lee, H.S.; Shin, J.W.; Park, M.S.; Ryu, H.-G. Probabilistic duration estimation model for high-rise structural work. *J. Constr. Eng. Manag.* **2009**, *135*, 1289–1298. [CrossRef]
7. Leu, S.S.; Hwang, S.T. Optimal repetitive scheduling model with shareable resource constraint. *J. Constr. Eng. Manag.* **2001**, *127*, 270–280. [CrossRef]
8. Petruseva, S.; Zileska-Pancovska, V.; Zujo, V. Predicting construction project duration with support vector machine. *Int. J. Res. Eng. Technol.* **2013**, *2*, 12–24.
9. Golizadeh, H.; Sadeghifam, A.N.; Aadal, H.; Majid, M.Z.A. Automated tool for predicting duration of construction activities in tropical countries. *KSCE J. Civ. Eng.* **2016**, *20*, 12–22. [CrossRef]
10. Erharter, G.H.; Marcher, T. On the pointlessness of machine learning based time delayed prediction of TBM operational data. *Autom. Constr.* **2021**, *121*, 103443. [CrossRef]

11. Statistical KOREA Government Office. Available online: http://www.index.go.kr/potal/main/EachDtlPageDetail.do?idx_cd=1242 (accessed on 25 March 2021).
12. Ministry of Land Infrastructure and Transport. *Housing Business Handbook*; Ministry of Land Infrastructure and Transport: Sejong-si, Korea, 2020.
13. Kim, O.H.; Cha, H.S. Development of quantitative decision support model for optimal form-work based on construction site type. *Korean J. Constr. Eng. Manag.* **2019**, *20*, 56–68.
14. Bnag, J.D.; Song, S.H.; Cho, G.H.; Sohn, J.R.; Kim, J.W. A study on non-working day calculation standards and days of non-working for estimation of optimum duration in the frame work of apartment building construction. *J. Archit. Inst. Korea Struct. Constr.* **2015**, *31*, 21–28. [CrossRef]
15. González, P.; González, V.; Molenaar, K.; Orozco, F. Analysis of causes of delay and time performance in construction projects. *J. Constr. Eng. Manag.* **2014**, *140*, 04013027. [CrossRef]
16. Castro-Lacouture, D.; Süer, G.A.; Gonzalez-Joaqui, J.; Yates, J.K. Construction project scheduling with time, cost, and material restrictions using fuzzy mathematical models and critical path method. *J. Constr. Eng. Manag.* **2009**, *135*, 1096–1104. [CrossRef]
17. Slootman, T. Planning of Mega-Projects: Influence of Execution Planning on Project Performance. Master's Thesis, University of Twente, Enschede, The Netherlands, 2007.
18. Hewage, K.N.; Ruwanpura, J.Y. Carpentry workers issues and efficiencies related to construction productivity in commercial construction projects in Alberta. *Can. J. Civ. Eng.* **2006**, *33*, 1075–1089. [CrossRef]
19. Seol, D.K.; Kim, D.Y.; Jeong, S.C.; Huh, Y.K. Determination model for optimum construction duration of apartment structural frameworks. *J. Archit. Inst. Korea Struct. Constr.* **2016**, *32*, 61–67. [CrossRef]
20. Bang, J.D.; Han, C.H.; Kim, S.K. Optimization of estimating duration of the structural frame for the high-rise apartment housing during the Winter season -focusing on one cycle time scheduling mechanism of the typical floor-. *Korean J. Constr. Eng. Manag.* **2005**, *5*, 170–178.
21. Park, J.H.; Kim, K.H.; KIM, J.J. Development for using stochastic construction scheduling model considering weather elements. *J. Archit. Inst. Korea Struct. Constr.* **2011**, *27*, 97–104.
22. Shin, J.W.; Rye, H.G.; Lee, H.S.; Park, M.S. Probabilistic Model to Forecast the Duration of Structural Work in High-rise Building Construction Considering Weather Elements. *J. Archit. Inst. Korea Struct. Constr.* **2007**, *23*, 123–132.
23. Altuwaim, A.; El-Rayes, K. Minimizing duration and crew work interruptions of repetitive construction projects. *Autom. Constr.* **2018**, *88*, 59–72. [CrossRef]
24. El-Abbasy, M.S.; Elazouni, A.; Zayed, T. MOSCOPEA: Multi-objective construction scheduling optimization using elitist non-dominated sorting genetic algorithm. *Autom. Constr.* **2016**, *71*, 153–170. [CrossRef]
25. Zhuge, H.; Cheung, T.; Pung, H. A timed workflow process model. *J. Syst. Softw.* **2001**, *55*, 231–243. [CrossRef]
26. Truong, N.K.V.; Choi, Y.; Kim, I.; Shin, S.; Hwang, W.J. A probabilistic approach to workflow time analysis for business process management. *Int. J. Comp. Sci.* **2009**, 797–801. Available online: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.193.3818&rep=rep1&type=pdf (accessed on 25 March 2021).
27. Shanmugasundaram, S.; Umarani, P. Queuing theory applied in our day to day life. *Int. J. Sci. Eng. Res.* **2015**, *6*, 533–541.
28. Civelek, I.; Biller, B.; Scheller-Wolf, A. Impact of dependence on single-server queueing systems. *Eur. J. Oper. Res.* **2021**, *290*, 1031–1045. [CrossRef]
29. Siddiqui, S.; Darbari, M.; Yagyasen, D. An QPSL queuing model for load balancing in cloud computing. *Int. J. Collab.* **2020**, *16*, 33–48. [CrossRef]
30. Teknomo, K. Queuing rule of thumb based on M/M/s queuing theory with applications in construction management. *Civ. Eng. Dimens.* **2012**, *14*, 139–146.
31. Ham, N.; Moon, S.; Kim, J.H.; Kim, J.J. Optimal BIM staffing in construction projects using a queueing model. *Autom. Constr.* **2020**, *113*, 103123. [CrossRef]
32. Little, J.D.C. A Proof of the Queuing Formula: $L = \lambda W$. *Oper. Res.* **1961**, *9*, 383–387. [CrossRef]