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Performance Analysis and Assessment of BIM-Based Construction Support with Priority Queuing Policy

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Abstract: A variety of methodological approaches have been developed to performance assessment for the adoption of building information modeling (BIM) at organizational and project levels. Recently, active research has been undertaken on the quantitative analysis of the effects of BIM on projects through BIM-based design validation methodologies. Nevertheless, few studies have addressed the interactions between the BIM staff providing BIM services and the project participants requesting BIM services from the viewpoint of micro-level management. In this study, with the aim of improving the performance of BIM-based construction support, we performed an analysis of the properties of the BIM request for information (RFI) in the construction phase, proposing a method for performance analysis and assessment which considers the competencies of the BIM staff that handle and process such requests. This study verified that, through the application of a priority policy according to the purpose of the information use in the construction phase, the performance of the BIM staff can be improved, and the waiting time of project participants to receive responses to the BIM RFIs can be reduced. The findings of this study are expected to be applied in areas such as decision making on allocation of BIM staff and analysis of return on investment (ROI) in hiring BIM services.

Keywords: BIM staff; BIM RFI; queuing model with priority; performance analysis and assessment

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1. Introduction

Building information modeling (BIM) plays an instrumental role as a technology that provides key information for the digital representation of construction projects [1]. Collaboration, coordination, and communication among construction project participants are necessary for quality decision making in a wide range of projects and tasks. This is the case not only for one-off tasks but also for tasks that are continuously carried out in a routine manner [2,3]. In addition, the roles and responsibilities of the BIM staff continue to expand owing to the diversity of requests for information (RFIs) from the BIM users who aim for active utilization of BIM [4]. BIM staff provide support in the process of decision making necessary for the actual implementation of a construction project, utilizing all data related to BIM (e.g., BIM model, 2D drawings, and bill of quantities) to support areas such as design review and changes, constructability review, interference review, quantity take-off and review, process review, safety management, shop drawing extraction, and visualization support [5–7].

To conduct performance analysis of BIM staff, Ham et al. (2020) developed an optimization technique wherein BIM users of a construction project who aim to utilize information from BIM, and the BIM staff responding to various types of RFIs from BIM, are modeled as customers and servers, respectively [8]. However, to verify the design documents in a short period of time, the performance was assessed with a focus on a project with application of BIM-based design validation. Therefore, this study aims to carry out a performance assessment that takes into account the characteristics of BIM-based construction support in the construction phase. The following factors are considered:

- Customer: Reflection of the properties (randomness) of BIM RFIs in the construction phase.
- Server: Reflection of the competencies (randomness) of BIM staff in the construction phase.
- Priority: Reflection of the priorities for each purpose of RFI by the project manager.
- Performance indicators: Presentation of micro-level BIM performance indicators.

For these purposes, the structure of this study is organized as follows. The literature review section includes not only a review of the existing related works on methods of measurement and assessment of BIM performance but also an analysis of the properties of the RFIs for BIM-based construction support and of previous studies on the queuing model, as well as a method for modeling the characteristics of these processes. The Section 3 seeks to clarify the properties of the RFIs described in the theory by using several cases of raised RFIs and responses to RFIs of BIM-based construction support recorded in the BIM monthly report of a real-world project. In the Research Method section, a model for deriving analysis results by reflecting the characteristics of BIM-based construction support analyzed through a review of the theoretical background is selected, and indicators for the analysis of performance and methods of interpretation are described. In addition, priorities for classifying the collected RFIs are presented in order to improve the performance of the BIM-based construction support. The Case Study section describes the data collection and analysis. RFIs, recorded in the monthly BIM report prepared in an actual BIM-based construction project, are processed and used as data for this study. In addition, information such as the average number of BIM staff members allocated for BIM-based construction support and the period elapsed is used with data from previous studies.

Finally, this study aims to conduct a performance analysis that comprehensively considers the queuing policy of giving priority to RFIs according to the purpose of information utilization, the characteristics of BIM users submitting RFIs, and the characteristics of the BIM staff responding to RFIs.

2. Literature Review

2.1. Performance Analysis and Assessment of BIM-Based Construction Projects

Previous studies have presented a variety of methods for the performance measurement of BIM. First, the tools for macro-level measurement of the maturity of BIM from organizational and project perspectives are as follows: bimSCORE [9], BIM Proficiency Matrix [10], BIM Interactive Capability Maturity Model (I-CMM) [11], BIM Maturity Measure (BIMmm) [12,13], BIM QuickScan [14], BIm3 [15], the macro-BIM adoption assessment model [16], and a success level assessment model for BIM projects [17]. Since these methodologies analyze the performance of BIM projects from a macroscopic perspective, there is a limit to analyzing the microscopic performance according to the input of BIM staff.

Second, studies that evaluate the positive impact of BIM adoption to construction projects through case studies are as follows. Both the analysis of return on investment (ROI) of BIM and the avoidance of economic losses due to design errors through BIM-based design validation were investigated [6,18]. Ham et al., (2018) classified the design errors identified through BIM-based design validation of high-rise construction projects into simple design errors, rework design errors (design errors likely to cause demolition and rework), and delay design errors (design errors likely to cause construction delay). Accordingly, the cost of loss due to design quality was quantified from the perspective of the contractor [18]. Lee et al., (2012) used BIM-based design validation for ROI analysis based on the rework costs that may be incurred [6]. Kim et al., (2017) quantified the value of BIM contribution to resolving issues that occurred in the construction phase [19]. In addition, Bryde et al., (2013) performed a qualitative analysis of various projects through the generation of success criteria and the use of context analysis for the project management body of knowledge [20]. In addition, some studies have performed qualitative and quantitative analysis on the ROI of the construction phase through various cases [21]. In summary, the existing methods of BIM performance assessment are applied to the macroscopic dimension of BIM implementation, which leads to the limitation that the assessment may depend on the subjective judgment of individual assessors.

Therefore, there is a need for an analysis method that allows the measurement of the performance of BIM-based construction support to further improve performances from macroscopic perspectives. To this end, this study aims to analyze the characteristics of the situations wherein the BIM staff receive and respond to RFIs from BIM users who aim for active utilization of BIM for the project in the construction phase.

2.2. Properties of Request for Information in BIM-Based Construction Support

BIM-based design validation, a methodology for reviewing design errors in the pre-construction phase, aims to minimize the impact on the construction phase by resolving the issue of the consistency of the BIM model and the quality of the drawings before fully embarking on the actual construction process [6,18]. Further, as previous studies reported that design errors can cause a significant loss in the construction phase, in order to prevent such loss, design validation is performed at the end of the working drawing phase or during a short period before the construction begins after entering the construction phase [6,18].

Collaboration on an ideal BIM-based construction project can be supported by modern BIM tools. For example, Solibri can maximize collaboration and solve problems by verifying BIM models or integrating models from various fields to assure quality [22]. Recently, tools such as BIMcollab and Revizto have been developed. These are tools that allow experts in various fields to collaborate, even in non-face-to-face situations, which supports live coordination beyond collaboration [23,24]. These tools not only verify the quality of the model, but also provide functions such as issue management and information exchange. If this BIM collaboration platform is used, various users can utilize the necessary information, as shown in Figure 1. Even if the BIM collaboration platform is introduced in the field, a BIM staff capable of operating this tool well is essential for many users to obtain the necessary information from BIM. If the BIM collaboration platform is not applied to the field, the BIM staff must perform the server role for collaboration between various users.

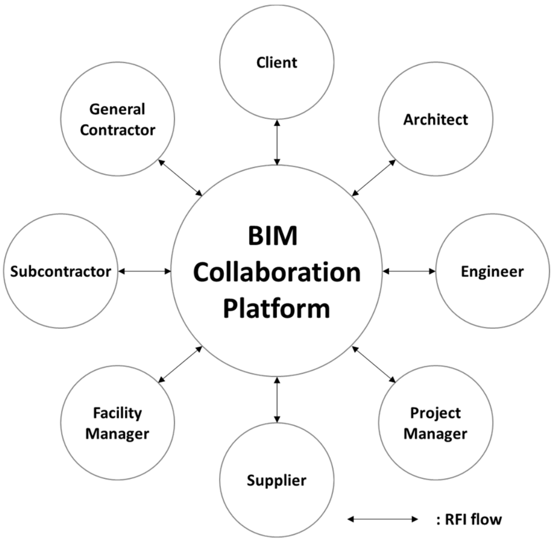

Figure 1. RFI flow in BIM collaboration platform.

In general, BIM-based design validation is performed with the input of a large BIM staff in a short period of time. In these cases, the focus is on resolving design errors through quality control of the drawings, and the types of design errors are classified into illogical design, discrepancies between drawings, and missing items [6]. In addition, because the BIM staff put into the project in support of the construction phase provide services during the construction period, there is the problem of a small number of staff members having to respond to BIM RFIs from many project participants. As discussed above, the BIM staffs' roles in responding to the BIM RFI requested by various users is very important, regardless of whether the BIM collaboration platform is used or not.

Ham et al. (2020) assumed the situation of waiting for the service described above, developed a queuing model and analyzed the performance of the system [8]. To analyze the adequacy of the BIM staffing level, the satisfaction with the service of project participants, who are customers waiting for a response to the BIM RFI they have raised, was considered. If BIM-based design validation has not been performed properly, the focus of BIM-based construction support must be on the design review and checking. Conversely, for the sites where BIM-based design validation has been properly performed, the validated BIM data can be utilized for decision making. Project participants who seek to utilize BIM actively request a wide variety of information types and formats for the purposes of decision making and as data for reporting in their work. Therefore, to respond to such information requests from project participants, BIM staff must have relevant competencies above a certain level, and a strategy for efficient responses to a wide range of requirements is needed. In this dimension, we aim to assess the performance of BIM staff through analysis methods that make it possible to consider various types of RFI from project participants, determine the number of BIM staff members in the project and their competencies, and analyze how much the performance can be improved through the application of a priority policy based on the purposes of RFIs.

2.3. Queuing Model

In the construction sector, various methodologies have been developed for the modeling of repeatedly performed work processes and the measurement of productivity. In particular, Halpin [25] developed the cyclic operation network (CYCLONE) to describe real job site processes. This is a management tool that enables productivity measurement and describes logical relationships between resources, operation time, and tasks in operations based on deterministic or probabilistic approaches [26]. Process modeling techniques and simulation systems based on CYCLONE include the resource queuing network simulation system (RESQUE) [27], construction object-oriented process simulation system (COOPS) [28], and state- and resource-based simulation of construction processes (Stroboscope) [29]. These methodologies are used to predict productivity through simulation, coordinate input resources through sensitivity analysis, and derive the optimal combination of resources. These methodologies can contribute to process optimization, but they have a limitation in that micro-level analysis for the quantitative effects of the allocation of input resources is not possible.

The measurement of work productivity from a microscopic point of view allows analysis on the effect of a given input (e.g., BIM staff) on the productivity of other inputs (e.g., project participants) [30]. Therefore, to perform micro-level analysis of the effect of the BIM staff on project participants, the interactions between these two stakeholders should be considered [31]. Work-flow management (WfM), which has been utilized since the early 1990s, facilitates improvements in the performance of business processes related to lead time, waiting time, service time, and resource utilization [32]. There are many different techniques for analyzing a WfM system [33–36]; among these methods, a queueing model that can generate numerical results is generally used [37,38]. Queuing theory describes a queuing system that can be observed in the real world [39]. Customers arrive at the queuing system individually and randomly to receive a service. If a customer cannot receive the service immediately upon arrival, the customer waits in the queue. Usually, one or more servers provide services. Each customer leaves the queuing system after receiving a service individually from a server [38]. Figure 2 expresses the waiting situation between the BIM staff supporting BIM collaboration and project participants who want to obtain RFI from BIM as a queue system that considers customers and servers.

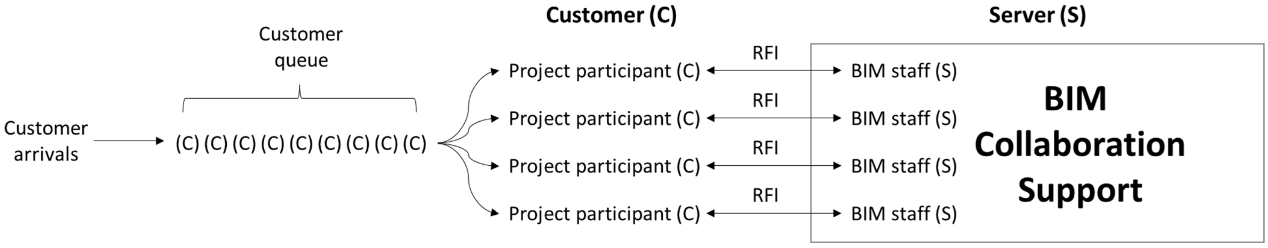

Figure 2. Queuing system supporting BIM collaboration.

Many of these queuing systems are characterized by time-dependent changes in parameters [40]. These time-dependent changes in parameters may have a substantial impact on the performance of queuing systems and should be considered in the design and control of these systems. Researchers from previous studies have applied the queuing model to various industries and sectors. The queuing model is applied to a wide range of decision making in sectors such as health care [41], emergency services [42,43], repair facilities [44], air traffic [45,46], transportation planning [47], and the management of container terminals [48]. However, in the construction sector, research with a queuing model is in the early stage of application for purposes such as the allocation of trucks for concrete work [49], performance measurement of BIM staff in their responses to BIM RFIs, and optimal BIM staffing [8,50].

In other fields of research, active studies have been performed to achieve improvement in the system performance through application of a priority policy for customers arriving at the queuing system. In the healthcare field, the waiting time of outpatients was minimized by coordinating their reservation time [51]. In the research of de Souza et al., (2015) for provision of patient care according to their medical seriousness, users with multiple priority classes were integrated into a system queue, and performance was evaluated for mean transfer time and mean waiting time for patients of different classes [52]. In the software field, the fault detection process and fault correction process of a system were improved by utilizing a priority queuing model [53]. In addition, Kim et al., (2013) analyzed the queue network of a call center and determined the priority of high-value customers to minimize damage to customer service [54]. Nan et al., (2014) compared the priority-service and multi-service scenarios to solve the resource optimization problem for a multimedia cloud, and through the comparison, derived the minimum response time for cloud resources and the minimum resource cost [55]. As can be observed from these prior studies in other research fields, it is possible to achieve improvement in the performance of systems where queuing occurs through changes in the policy of responding to customers' requests at the microscopic level. However, there are few research methodologies and empirical cases in the construction industry.

3. Problem Statements in BIM-Based Construction Support

In this section, RFI properties for the BIM-based construction support reviewed in the previous section of theoretical background are examined through records of BIM-based construction support applied in a real-world construction project. The image on the left of Figure 3 shows the communication method used when a project participant requests a BIM RFI from the BIM staff to visualize and review safety facilities before installation. As a non-expert on BIM, the project participant asks for information roughly by highlighting a section on the printed 2D drawing with a highlighter. The BIM staff, which received such a rough request, provide modeling and 3D visualization data for safety facilities requested in the existing BIM model, as shown in the right image of Figure 3.

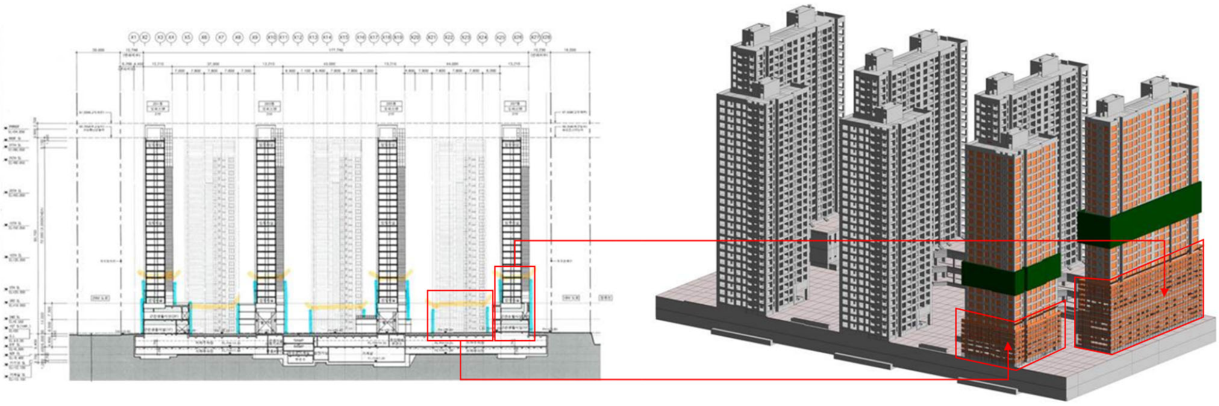

Figure 3. A case of BIM RFI: (**left**) visualization request for safety facility (**right**) visual representation using BIM model.

The BIM RFIs occurring at the construction site require not only extraction of reference information (e.g., quantity, level, and location) from BIM but also additional modeling of hypothetical construction equipment, which often involves a wide scope of work, so that the project participants can receive and check the requested information. In addition, responses to BIM RFIs may involve the extraction of 2D or 3D views from a BIM model or the representation of information through linking with a shop drawing on site, shown as Figure 4. Thus, the response time may be very short for some RFIs but considerably longer for some other types of RFIs.

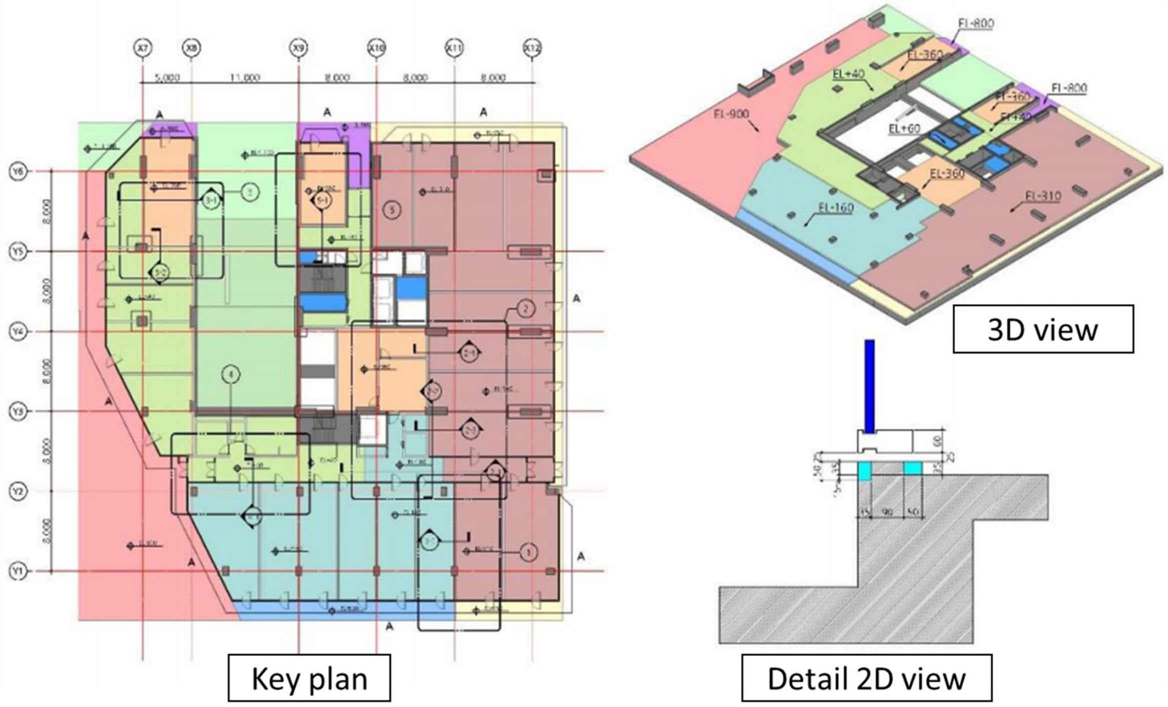

Figure 4. A review case of level utilizing a combination of detailed information included in a floor plan, 3D view, and 2D detail drawing.

In addition to a variety of properties of individual BIM RFIs, when the construction process is assumed to be a production system, the BIM staff for BIM-based construction support has to bear the uncertainties that stem from not knowing in advance what type of BIM RFIs will be raised by the project participants. Additionally, an accurate estimation for time of responses to BIM RFIs is also not possible. Because only a small number of BIM staff members are put in the construction project to respond to the BIM RFIs from many project participants, waiting in a queue is unavoidable depending on the performance of the BIM staff. This can determine the level of satisfaction of the project participants with the BIM service; therefore, the management of BIM-based construction support is required in this aspect.

Therefore, it is necessary to consider appropriate criteria for setting priorities to achieve improvement in the work performance of a limited number of BIM staff members in terms of responses to the BIM RFIs of various project participants. The criteria for setting priorities would be to prioritize BIM RFIs that can have a significant impact on the achievement of the project's goals and targets. BIM-based construction support includes constructability review, process review, design review and changes, quantity take-off and review, interference review, shop drawing review, safety management, and other steps (e.g., visualization).

To respond to the BIM RFI, the BIM staff should frequently manage the version of the original BIM model that can be updated. Among different modes of information utilization for BIM-based construction support, design review and changes have the greatest impact on the change of shape and property information of a BIM model adopted in real construction projects. Design validation also serves as the standard for the extraction of BIM data for other information use purposes; therefore, it has the highest importance among the different purposes of information utilization. In a previous study, a case wherein the BIM-based construction support merely focused on correcting design errors was reported; in that case, the BIM-based design validation was not carried out properly [8]. In this study, BIM RFIs are classified by different purposes of use of the requested information, and we aim to investigate how a policy of handling BIM RFIs according to priorities can improve the performance of BIM staff.

4. Research Method

4.1. M/M/s Queuing Model with Priority

In a queuing system, the time between the arrival of a customer and arrival of the next customer is referred to as the inter-arrival time, and if sufficient data of customer arrivals are collected, the average number of customers arriving per unit time can be estimated. This is referred to as the mean arrival rate and is denoted by λ. In most cases, queuing models assume an exponential distribution as a probability distribution for inter-arrival time. Because of the large variability of inter-arrival times, a prediction of when the next customer will arrive is not possible, which is why this is also referred to as random arrival. An estimate of the mean inter-arrival time is equal to $1/\lambda$.

The time elapsed from the moment a customer starts receiving a service to the moment the service is completed is referred to as the service time. Here, the average number of customers for which one server completes the service per unit time under the assumption of non-stop work of the server is referred to as the mean service rate. This is denoted as μ. Service time generally varies depending on the type of service requested by the customer. Exponential distribution is a representative probability distribution for service time in a queuing system. This indicates that in most cases, the service time is short, that but in rare cases it can be very long. Therefore, the estimate of the mean service time is equal to $1/\mu$.

In a previous study, the M/M/s model, which is a multiple-server queuing model, was used. This model considers the characteristics of the queuing system for project participants requesting BIM RFIs and the service competencies of the BIM staff responding to BIM RFIs [8]. In a basic queuing system, each customer (i.e., project participant) is served individually by one server (BIM staff). According to the number of servers, the queuing system is classified into the M/M/1 model, which is a single-server system, and the M/M/s model, which is a multiple-server system. Although there are a variety of queuing models according to the probabilities of customer arrival time and service time, the project participants who request BIM RFIs are assumed to be customers that arrive at the system randomly. Because the service time of the BIM staff responding to a BIM RFI could be very long or very short, this uncertainty is reflected in the assumptions. This study utilizes the M/M/s model, and the assumptions applied to the existing M/M/s model are summarized as follows:

- The inter-arrival times are distributed independently and equally, depending on the probability distribution.
- All arriving customers enter the queue system and stay there until service is complete.
- The queuing system has one infinite queue. Thus, it can accommodate an infinite number of customers.
- The queuing rule is first come, first served (FCFS).
- There is a fixed number of servers in the queuing system, and each server can serve any customer.
- Each customer is served individually by one server.
- Service times are distributed independently and identically according to the specified probability distribution.

The distinctive contribution in the methodology proposed in this study is that the rules applied to the queuing system are based on priorities of RFIs. In a queuing model with priorities, the queuing rules are based on priorities. Therefore, the order of selecting customers from the queues for service is determined by a preset rule of priority (by purpose of information utilization). In practice, a queuing model based on such rules of priorities is much more suitable for many queuing systems. The tasks that need to be handled with priority are processed first, and priorities can be given to important customers over others. There are two types of queuing models with a priority rule. Both models assume that there are N priority levels (level 1 indicates the highest priority, and level N is the lowest priority), and when one server can serve one customer in the queue, the highest priority among customers is given to the one that has waited the longest and the customer is selected and served. This indicates that the server selects customers in the order of priority level; for customers in the same priority level, the customer is then selected on a FCFS basis. The distribution of inter-arrival time and service time for each priority level is assumed to be an exponential distribution.

The difference between the two models is whether the priorities are non-preemptive or preemptive. Non-preemptive priorities refer to the cases when a high-priority customer arrives in the system and a low-priority customer continues to be served until the service ends. Therefore, once the server starts serving a customer, the service is not interrupted until it is complete. The first model is a model with non-preemptive priorities. Preemptive priorities refer to cases whereby a higher-priority customer arrives at the system and the lower-priority customer in service is evicted (returned to the queue). Then, the server immediately starts serving the newly arrived high-priority customer. After completing the service, the server selects a customer according to the priority rules described above, and the evicted customer receives the service multiple times repeatedly until the service is completed. This study comparatively analyzes the performance of the BIM staff in the cases when FCFS, the conventional queuing rule, is applied and when non-preemptive priorities and preemptive priorities are applied.

4.2. Performance Indicators of M/M/s Queuing Model

The performance of the M/M/s model can be assessed in terms of (1) how many customers are waiting in the queuing system and (2) how long they wait in the queue. To analyze the performance in these aspects, four specific performance indicators are defined as follows.

L: No. of tasks in the system
L_q: No. of tasks in the queue
W: Average waiting time of each customer in the system
W_q: Average waiting time of each customer in the queue

The basic equations for deriving L, L_q, W, and W_q in a multiple-server queuing model are presented as Equations (1)–(5).

$$P_0 = \frac{1}{\sum_{n=0}^{s-1} \frac{(\lambda/\mu)^n}{n!} + \frac{(\lambda/\mu)^s}{s!}\left(\frac{1}{1-\lambda/s\mu}\right)} \tag{1}$$

$$L_q = \frac{P_0(\lambda/\mu)^s \rho}{s!(1-\rho)^2} = \frac{P_0 \lambda^{s+1}}{(s-1)!\mu^{s-1}(s\mu-\lambda)^2} \tag{2}$$

$$W_q = L_q/\lambda \tag{3}$$

$$W = W_q + \frac{1}{\mu} \tag{4}$$

$$L = \lambda W\ (\lambda :\ mean\ arrival\ rate). \tag{5}$$

The most important equation for calculating the basic performance magnitudes in the queuing model is Little’s formula, Equation (5), which demonstrates the direct relationship between L and W [56] and holds for L_q and W_q. If any of L, L_q, W, and W_q ar analyzed, the remaining performance magnitudes can be obtained immediately, thus allowing for an analysis of the service’s basic status. Even with the application of the priority rules, this formula can be applied in the same way. The difference is in the distribution of waiting time derived by assuming the FCFS rule. With a new priority rule, the variance of this distribution becomes much larger. This is because the waiting time of the customer with the highest priority is substantially reduced compared to that with the FCFS rule, and the waiting time of the customer with the lowest priority increases (we aim to improve the performance indicators for high-priority customers at the expense of the performance indicators for low-priority customers).

4.3. Performance Indicators of M/M/s Queuing Model with Priority

Performance measures, such as average waiting time and mean number of customers in the queuing system, should be derived according to the priority level. In the steady state of the non-preemptive priorities model, if the average waiting time in the system for a customer with priority level k is W_k, the following can be derived Equations (6)–(11).

$$W_k = \frac{1}{AB_{k-1}B_k} + \frac{1}{\mu},\ k = 1, 2,\ \ldots,\ N \tag{6}$$

$$A = s!\frac{s\mu-\lambda}{r^s}\sum_{j=0}^{s-1}\frac{r^j}{j!} + s\mu \tag{7}$$

$$B_0 = 1, \tag{8}$$

$$B_k = 1 - \frac{\sum_{i=1}^{k}\lambda_i}{s\mu}, \tag{9}$$

$s = Number\ of\ servers$
$\mu = Mean\ service\ rate\ per\ server$
$\lambda_i = Mean\ arrival\ rate\ for\ level\ i\ customer$

$$\lambda = \sum_{i=1}^{N}\lambda_i, \tag{10}$$

$$\rho = \frac{\lambda}{\mu}. \tag{11}$$

This result is based on the assumption that $\sum_{i=1}^{k}\lambda_i < s\mu$. Thus, a level k customer can reach a steady state. Because Little’s formula can be applied to each priority level, L_k is referred to as the mean number of customers of priority level k in the queuing system at a steady state. Then, we have

$$L_k = \lambda_k W_k,\ \ k = 1, 2,\ \ldots,\ N.$$

The average waiting time in the queue for priority level k customer is obtained by μ the special case of $s = 1$, we reach $A = \frac{\mu^2}{\lambda}$. In this study, priority was applied to the M/M/1 model, which is a special case of the M/M/s model with s = 1.

In the non-preemptive priorities model with a single server, the assumption that the mean service time of all priority level is equal to $1/\mu$ is highly restrictive. This assumption is not appropriate because the service requests from different levels of priorities are different. Fortunately, in the case of a single server, useful results can be obtained even when the mean service time is different for each level. Let μ_k be the mean of service times for class k customer. That is,

$$\mu_k = mean\ service\ rate\ for\ level\ k,\ k = 1, 2, \ldots,\ N$$

Then, the average waiting time in the system for priority level k customer in the steady state is represented as follows in Equations (12)–(17)

$$W_k = \frac{a}{b_{k-1} b_k} + \frac{1}{\mu_k},\ k = 1, 2,\ \ldots,\ N \tag{12}$$

$$a_k = \sum_{i=1}^{k} \frac{\lambda_i}{\mu_i^2} \tag{13}$$

$$b_0 = 1 \tag{14}$$

$$b_k = 1 - \sum_{i=1}^{k} \frac{\lambda_i}{\mu_i} \tag{15}$$

In this result, the following is assumed so that the level k customer can reach a steady state. Little's formulas can be used to calculate other key performance indicators

$$\sum_{i=1}^{k} \frac{\lambda_i}{\mu_i} < 1, \tag{16}$$

For the preemptive priorities model, it is assumed that the mean service time is the same for all priority levels. If the same symbols as those in the non-preemptive priorities model are used, the total average waiting time in the system is changed as follows in the case of a single server owing to the application of preemptive priorities.

$$W_k = \frac{1/\mu}{B_{k-1} B_k},\ k = 1, 2,\ \ldots,\ N. \tag{17}$$

5. Case Study

5.1. Project Description and Data Collection

In this study, performance analysis is conducted which focuses on the task of BIM-based construction support in the construction phase. For this purpose, a monthly BIM report was obtained wherein the BIM RFIs in the construction phase are recorded, and data for this study were collected. The company with the monthly report data provided BIM-based construction support for more than 15 years. In particular, regardless of whether BIM-based design validation is implemented up to the working drawings phase, BIM-based design validation from the contractor's point of view is carried out at the early stage of the construction phase. Based on these data, BIM-based construction support is carried out, and a strategy of having a minimum number of BIM staff members resident on site is applied. In addition, the BIM staff continuously records the BIM RFIs requested by project participants in the construction phase through the monthly BIM reports. In the case of the construction phase, given that the project execution period is long, project participants submit BIM RFIs to the BIM staff at weekly and monthly process meetings or off-the-cuff meetings. For BIM RFIs of importance, they are recorded through the monthly BIM report prepared in the construction phase. For this study, 872 BIM RFI data of four completed projects out of 2766 BIM RFI cases recorded at a total of 12 sites were used. In the four projects, the monthly BIM report was prepared for an average period of 16.5 months, and during this period, one BIM staff member responded to the BIM RFIs in the construction phase. In this study, the BIM RFIs were classified according to the purpose of use of the requested information for the classification of priorities of BIM RFIs. The purpose of BIM information use was classified into the following categories: constructability review, process review, design review and changes, quantity take-off and review, interference review, shop drawing review, safety management, and others (e.g., visualization). Accordingly, data were collected based on categories of construction type (Table 1), source of information (Table 2), and information type (Table 3).

Table 1. Classification of construction types for BIM RFIs by purpose of information use.

Purpose of BIM Information Use	Construction Type					
	Earthwork	Foundations	Framing	Finishing	Mechanical, Electrical, and Plumbing	Total
Constructability review	13	6	56	37	49	161
Process review	3	7	111	5	1	127
Design review and changes	1	0	168	53	40	262
Quantity take-off and review	2	13	126	57	0	198
Interference review	1	0	15	5	49	70
Shop drawing review	0	0	8	14	2	24
Safety management	0	0	8	14	3	25
Others (visualization, etc.)	0	0	4	0	1	5
Total	20	26	496	185	145	872

Table 2. Classification of information sources for the BIM RFIs by purpose of information use.

Purpose of BIM Information Use	Source of Information				
	Revit	Navisworks	AutoCAD	etc. (xlsx)	Total
Constructability review	132	22	26	9	161
Process review	52	72	2	5	127
Design review and changes	186	35	126	0	262
Quantity take-off and review	149	10	4	46	198
Interference review	32	36	12	0	70
Shop drawing review	13	4	14	1	24
Safety management	15	9	0	1	25
Others (visualization, etc.)	2	0	4	0	5
Total	581	188	188	62	1019

Table 3. Classification of information types for the BIM RFIs by purpose of information use.

Purpose of BIM Information Use	Type of Information				
	2D Information	3D Information	4D Information	Combination of 2D, 3D, and 4D Information	Total
Constructability review	41	78	0	42	161
Process review	8	84	21	14	127
Design review and changes	98	52	0	112	262
Quantity take-off and review	25	69	2	102	198
Interference review	5	52	0	13	70
Shop drawing review	9	7	0	8	24
Safety management	6	18	0	1	25
Others (visualization, etc.)	3	1	0	1	5
Total	195	361	23	293	872

In terms of classification according to the construction type, where project participants raised BIM RFIs to the BIM staff, the frequency of BIM RFIs was high in the order of framing, finishing, and installation of facilities (mechanical, electrical, and plumbing) (Table 1). To respond to the BIM RFIs from a variety of project participants, the BIM staff should not only utilize the BIM authoring tool (e.g., Revit). Rather, they should make use of other programs such as AutoCAD and Excel with a focus on a BIM simulation tool (e.g., Navisworks). From these various types of information processing, the frequency of utilizing BIM authoring tools, which are required to revise and update the BIM model, was high (Table 2). The data in Table 2 reveals that many different sources of information are used to respond to BIM RFIs. As can be observed in Table 3, responses to BIM RFIs are made by utilizing various types of information such as 2D, 3D, and 4D information. In particular, the frequency of utilizing a combination of 2D, 3D, and 4D information is high.

In this study, considering these properties of BIM RFIs, we aim to apply a priority policy according to the purpose of information use. As discussed in the review of theoretical background in previous sections, when BIM-based construction support is carried out without properly conducting BIM-based design validation, the BIM staff has to be continuously allocated to design review tasks rather than construction support [8]. In addition, as a result of the analysis based on the classified data of BIM RFIs, it can be determined that the continuous management of the shape of the BIM model is as important in the construction phase as in the design phase. Therefore, in this study, the priority of design review and changes was set to Level 1, and the priority of constructability review, process review, and quantity take-off and review, which show high frequency among the purposes of information utilization in the construction phase, was set to Level 2. Finally, the priority of interference review, shop drawing review, safety management, and others (e.g., visualization) was set to Level 3 (Table 4). This study aims to analyze how the performance of the BIM staff responding to BIM RFIs is improved when the above-described priority policy is applied. To this end, the performance indicators of the queuing model are used.

Table 4. Classification of priority by purpose of information use.

Priority	Purpose of Information Use	Earthwork	Foundations	Framing	Finishing	Mechanical, Electrical, and Plumbing	Total
Level 1	Design review and changes	1	0	168	53	40	262
Level 2	Constructability review	13	6	56	37	49	161
	Process review	3	7	111	5	1	127
	Quantity take-off and review	2	13	126	57	0	198

Table 4. *Cont.*

Priority	Purpose of Information Use	Earthwork	Foundations	Framing	Finishing	Mechanical, Electrical, and Plumbing	Total
Level 3	Interference review	1	0	15	5	49	70
	Shop drawing review	0	0	8	14	2	24
	Safety management	0	0	8	14	3	25
	Others (visualization, etc.)	0	0	4	0	1	5

5.2. Data Analysis

Table 5 presents a summary of the basic parameters used for analyzing the performance of the BIM staff using the M/M/s model, which were previously set. First, in the queuing model under the FCFS rule, assuming that 872 BIM RFIs could be processed in 16.5 months, the mean arrival rate (λ) of the BIM RFIs was 2.03. Meanwhile, when the priority rule was applied, the mean arrival rate (λ_1) of BIM RFIs belonging to the Level 1 priority group was set to 0.61, the mean arrival rate (λ_2) of BIM RFIs belonging to the Level 2 priority group was set to 1.13, and the mean arrival rate (λ_3) of BIM RFIs belonging to the Level 3 priority group was set to 0.29. The mean service rate (μ) for the BIM RFIs in the construction phase was set to 3 after considering the competencies of the BIM staff in the previous study [8]. ρ (= $\lambda/s\mu$), the service utilization factor, was 0.6775, indicating that the service state is stable. This means that the BIM staff is busy for 67.75% of the working hours of the day. In previous studies, the ρ value at optimal allocation of the BIM staff was in the range of 0.33 to 0.76 [8]. Therefore, the case site of this study can be judged as a site where stable operations were carried out. However, this value is greatly influenced by the number of BIM staff committed to respond to the BIM RFI of project participants. In addition, it should be considered that this may change depending on whether BIM-based design validation is performed in the design stage.

Table 5. Definition of parameters for the performance analysis.

Parameter	Value	Description
λ	2.03	Mean arrival rate
λ_1	0.61	Mean arrival rate of priority level 1
λ_2	1.13	Mean arrival rate of priority level 2
λ_3	0.29	Mean arrival rate of priority level 3
μ	3	Mean service rate
s	1	Number of servers
$\rho = \lambda/s\mu$	0.6775	Utilization factor

Table 6 lists the results of the analysis with the model of the proposed research methodology using the parameters summarized in Table 5. When the priority policy is applied and the order of service varies according to the priority level, the service utilization factor does not change in the overall queuing model. As discussed in the review of the theoretical background, the priority rule aims to maximize the satisfaction of customers with high priority level by sacrificing customers with low-priority level. In addition, the resources and competencies of the BIM staff can be focused on customers with a high priority level. Compared to the case of healthcare or emergency services sectors, in BIM-based construction support, customers belonging to the group whose priority is sacrificed do not have a considerable impact on the overall system performance. In fact, comparing the L, Lq, W, and Wq values with application of FCFS rule and with application of the priority rule, the W value of the Level 1 group with high priority is improved from 1.0337 to 0.6169 with non-preemptive priorities, and from 1.0337 to 0.4185 with preemptive priorities. In addition, the value of Wq is also significantly improved from 0.7004 to 0.2836 in the case of non-preemptive priorities, and from 0.7004 to 0.0852 in the case of preemptive priorities. As can be observed from these values, when priority rules are applied, the BIM staff can process the service for BIM RFIs belonging to the group with high importance, and compared to the policy of non-preemptive priorities, the policy of preemptive priorities improves the service performance to a greater extent for customers with high priority level.

Table 6. Comparison of performance indicators of the queuing model with different priority levels.

Performance Indicator	First Come First Served (FCFS)	Non-Preemptive Priorities			Preemptive Priorities		
		Priority Level 1	Priority Level 2	Priority Level 3	Priority Level 1	Priority Level 2	Priority Level 3
L	2.1012	0.3768	1.1447	0.5797	0.2556	1.1321	0.7134
L_q	1.4237	0.1732	0.7671	0.4834	0.0520	0.7545	0.6171
W	1.0337	0.6169	1.0104	2.0057	0.4185	0.9994	2.4683
W_q	0.7004	0.2836	0.6771	1.6724	0.0852	0.6660	2.1350
$\rho = \lambda/s\mu$	0.6775	0.6775	0.6775	0.6775	0.6775	0.6775	0.6775

Figures 5 and 6 show the changes in the performance of work for Level 2 and Level 3 customers belonging to the low-priority group. The result shows that the response service for BIM RFIs belonging to the Priority Level 2 group showed a slight improvement in dealing with non-preemptive priorities compared to the application of the FCFS rule. However, the results show that the response service for BIM RFIs belonging to the Priority Level 3 group was worsened almost two-fold, with the W value increasing from 1.0337 to 2.0057 and the Wq value increasing from 0.7004 to 1.6724.

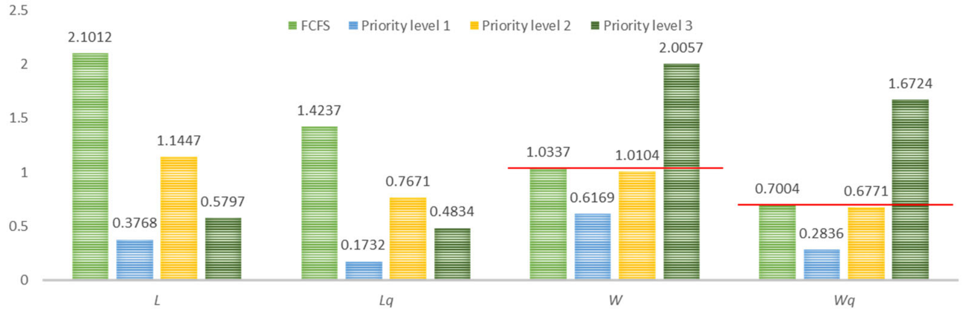

Figure 5. Comparison of performance indicators: FCFS rule vs. non-preemptive priorities.

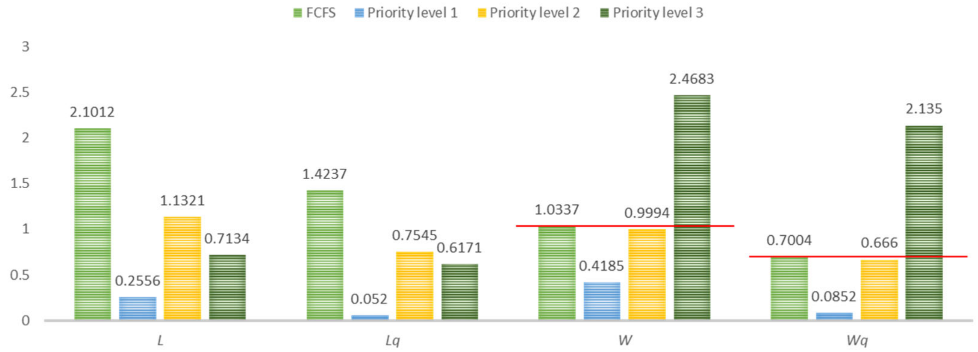

Figure 6. Comparison of performance indicators: FCFS rule vs. preemptive priorities.

In the model with preemptive priorities, the result shows that the response service to the BIM RFIs belonging to the Priority Level 2 group showed a slight improvement compared to the application of the FCFS rule. This was similar to the result of the model with non-preemptive priorities. However, the response service for BIM RFIs belonging to the Priority Level 3 group worsened even more than that of the non-preemptive priorities model, with the W value changing from 1.0337 to 2.4683 and Wq value from 0.7004 to 2.135. There are 124 BIM RFIs belonging to the Priority Level 3 group in total, which do not account for a large proportion of the total BIM RFIs of 872 and do not have a significant impact on the project performance. Therefore, not only the model with non-preemptive priorities but also that with a policy of preemptive priorities can be adopted as strategies for BIM-based construction support.

6. Discussion and Conclusions

To improve the performance of BIM-based construction support, this study analyzed the properties of BIM RFIs in the construction phase and proposed a performance analysis and assessment method which considers the competencies of the BIM staff handling BIM RFIs. In particular, through the application of the priority policy according to the purpose of information utilization in the construction phase, both the performance of responses to BIM RFIs by the BIM staff and the satisfaction of project participants waiting for responses to the requested BIM RFIs were analyzed by using the performance indicators of the queuing model. In addition, the existing queuing model methodology applied to the BIM-based design validation was extended to reflect the context of BIM-based construction support. The findings of this study can be utilized as the added business value of BIM in decision making for BIM staffing, and for research on BIM ROI analysis.

The value and significance of the present study lie in the fact that the study aims to maintain the continuity of information in the construction phase, regardless of the BIM implementation status in the design phase. The project participants, who are BIM users, may actively utilize the BIM until the end of the project depending on the competencies of the BIM staff providing BIM services, otherwise they may be disappointed with BIM. From a qualitative perspective, this study assumed the interaction between the BIM staff and project participants to be a single queuing system, and performed analysis and assessment of this system through a proven methodology of business management science. Furthermore, this study also contributed to verifying the effectiveness of the priority policy to improve the performance of the allocated input of the limited BIM staff resources.

The findings of this study can be utilized in decision making for the allocation of an optimal size of BIM staff when two or more BIM staff members are involved in the project. In addition, to maximize the ROI of a project with the adoption of BIM, the waiting time can be converted to cost and can be effectively applied for decision making.

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References

1. Sacks, R.; Eastman, C.; Lee, G.; Teicholz, P. *BIM Handbook: A Guide to Building Information Modeling for Owners, Designers, Engineers, Contractors, and Facility Managers*; John Wiley & Sons: Hoboken, NJ, USA, 2018.
2. Shen, F.Y.; Chang, A.S. Exploring coordination goals of construction projects. *J. Manag. Eng.* **2011**, *27*, 90–96. [CrossRef]
3. De Saram, D.D.; Ahmed, S.M.; Anson, M. Suitability of the critical incident technique to measure quality of construction coordination. *J. Manag. Eng.* **2004**, *20*, 97–109. [CrossRef]
4. Forcael, E.; Martínez-Rocamora, A.; Sepúlveda-Morales, J.; García-Alvarado, R.; Nope-Bernal, A.; Leighton, F. Behavior and performance of BIM users in a collaborative work environment. *Appl. Sci.* **2020**, *10*, 2199. [CrossRef]
5. Merschbrock, C.; Munkvold, B.E. Effective digital collaboration in the construction industry—A case study of BIM deployment in a hospital construction project. *Comput. Ind.* **2015**, *73*, 1–7. [CrossRef]
6. Lee, G.; Park, H.K.; Won, J. D3 City project—Economic impact of BIM-assisted design validation. *Autom. Constr.* **2012**, *22*, 577–586. [CrossRef]

7. Howard, R.; Björk, B.C. Building information modelling—Experts' views on standardisation and industry deployment. *Adv. Eng. Inform.* **2008**, *22*, 271–280. [CrossRef]
8. 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]
9. bimSCORE. bimSCORE Official Website. 2012. Available online: www.bimscore.com (accessed on 24 October 2022).
10. *IU BIM Proficiency Matrix*; Indiana University Architect's Office: Bloomington, IN, USA, 2009.
11. McCuen, T.L.; Suermann, P.C.; Krogulecki, M.J. Evaluating award-winning BIM projects using the national building information model standard capability maturity model. *J. Manag. Eng.* **2012**, *28*, 224–230. [CrossRef]
12. Arup. The Arup BIM Maturity Measure. 2016. Available online: https://www.arup.com/perspectives/publications/research/section/bim-maturity-model (accessed on 3 January 2023).
13. Duncan, A.; Aldwinckle, G. *BM6460—How to Measure the Impact of Building Information Modeling on Your Business*; Autodesk University: San Francisco, CA, USA, 2014.
14. Sebastian, R.; van Berlo, L. Tool for benchmarking BIM performance of design, engineering and construction firms in the Netherlands. *Archit. Eng. Des. Manag.* **2010**, *6*, 254–263. [CrossRef]
15. Underwood, J.; Isikdag, U. (Eds.) *Handbook of Research on Building Information Modeling and Construction Informatics: Concepts and Technologies: Concepts and Technologies*; IGI Global: Hershey, PA, USA, 2009; pp. 65–102.
16. Succar, B.; Kassem, M. Macro-BIM adoption: Conceptual structures. *Autom. Constr.* **2015**, *57*, 64–79. [CrossRef]
17. Won, J.; Lee, G. How to tell if a BIM project is successful: A goal-driven approach. *Autom. Constr.* **2016**, *69*, 34–43. [CrossRef]
18. Ham, N.; Moon, S.; Kim, J.H.; Kim, J.J. Economic analysis of design errors in BIM-based high-rise construction projects: Case study of Haeundae L project. *J. Constr. Eng. Manag.* **2018**, *144*, 05018006. [CrossRef]
19. Kim, S.; Chin, S.; Han, J.; Choi, C.H. Measurement of construction BIM value based on a case study of a large-scale building project. *J. Manag. Eng.* **2017**, *33*, 05017005. [CrossRef]
20. Bryde, D.; Broquetas, M.; Volm, J.M. The project benefits of building information modelling (BIM). *Int. J. Proj. Manag.* **2013**, *31*, 971–980. [CrossRef]
21. Neelamkavil, J.; Ahamed, S.S. *The Return on Investment from BIM-Driven Projects in Construction*; National Research Council of Canada: Ottawa, ON, Canada, 2012.
22. Solibri—BIM Software—For Architects and Engineers. Available online: http://www.solibri.com/ (accessed on 19 December 2022).
23. BIMcollab: Model Validation and Issue Management for BIM. Available online: http://www.bimcollab.com (accessed on 19 December 2022).
24. Revizto. Available online: https://revizto.com (accessed on 19 December 2022).
25. Halpin, D.W. CYCLONE—Method for modeling job site processes. *J. Constr. Div.* **1977**, *103*, 489–499. [CrossRef]
26. Halpin, D.W.; Riggs, L.S. *Planning and Analysis of Construction Operations*; John Wiley & Sons: Hoboken, NJ, USA, 1992; ISBN 978-0-471-55510-0.
27. Chang, D.M. RESQUE: A resource based simulation system for construction process planning. Diss. Ph.D. Thesis, University of Michigan, Ann Arbor, MI, USA, 1986.
28. Liu, L.Y. COOPS: Construction Object-Oriented Simulation System. Ph.D. Thesis, University of Michigan, Ann Arbor, MI, USA, 1991.
29. Martinez, J.C. STROBOSCOPE: State and Resource Based Simulation of Construction Processes. Ph.D. Thesis, University of Michigan, Ann Arbor, MI, USA, 1996.
30. Halligan, D.W.; Demsetz, L.A.; Brown, J.D.; Pace, C.B. Action-response model and loss of productivity in construction. *J. Constr. Eng. Manag.* **1994**, *120*, 47–64. [CrossRef]
31. Bernolak, I. Effective measurement and successful elements of company productivity: The basis of competitiveness and world prosperity. *Int. J. Prod. Econ.* **1997**, *52*, 203–213. [CrossRef]
32. Reijers, H.A.; Van Der Aalst, W.M. The effectiveness of workflow management systems: Predictions and lessons learned. *Int. J. Inf. Manag.* **2005**, *25*, 458–472. [CrossRef]
33. Chang, D.H.; Son, J.H.; Kim, M.H. Critical path identification in the context of a workflow. *Inf. Softw. Technol.* **2002**, *44*, 405–417. [CrossRef]
34. Li, H.; Yang, Y. Dynamic checking of temporal constraints for concurrent workflows. *Electron. Commer. Res. Appl.* **2005**, *4*, 124–142. [CrossRef]
35. Son, J.H.; Kim, J.S.; Kim, M.H. Extracting the workflow critical path from the extended well-formed workflow schema. *J. Comput. Syst. Sci.* **2005**, *70*, 86–106. [CrossRef]
36. Zhuge, H.; Cheung, T.Y.; Pung, H.K. A timed workflow process model. *J. Syst. Softw.* **2001**, *55*, 231–243. [CrossRef]
37. Jeong, K.Y.; Cho, H.; Phillips, D.T. Integration of queueing network and IDEF3 for business process analysis. *Bus. Process Manag. J.* **2008**, *14*, 471–482. [CrossRef]
38. 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. Hum. Soc. Sci.* **2010**, *5*, 811–815.
39. Hiller, F.; Hiller, M. *Introduction to Management Science: A Modeling and Case Studies Approach with Spreadsheets*, 4th ed.; McGraw-Hill Education: New York, NY, USA, 2010; ISBN 007809660X.

40. Schwarz, J.A.; Selinka, G.; Stolletz, R. Performance analysis of time-dependent queueing systems: Survey and classification. *Omega* **2016**, *63*, 170–189. [CrossRef]
41. Gillard, J.; Knight, V. Using Singular Spectrum Analysis to obtain staffing level requirements in emergency units. *J. Oper. Res. Soc.* **2014**, *65*, 735–746. [CrossRef]
42. Kolesar, P.J.; Rider, K.L.; Crabill, T.B.; Walker, W.E. A queuing-linear programming approach to scheduling police patrol cars. *Oper. Res.* **1975**, *23*, 1045–1062. [CrossRef]
43. Bookbinder, J.; Martell, D. Time-dependent queueing approach to helicopter allocation for forest fire initial-attack. *Inf. Syst. Oper. Res.* **1979**, *17*, 58–70. [CrossRef]
44. Jung, W. Recoverable inventory systems with time-varying demand. *Prod. Invent. Manag. J.* **1993**, *34*, 77.
45. Koopman, B.O. Air-terminal queues under time-dependent conditions. *Oper. Res.* **1972**, *20*, 1089–1114. [CrossRef]
46. Bookbinder, J. Multiple queues of aircraft under time-dependent conditions. *Inf. Syst. Oper. Res.* **1986**, *24*, 280–288. [CrossRef]
47. Chakroborty, P.; Gill, R.; Chakraborty, P. Analysing queueing at toll plazas using a coupled, multiple-queue, queueing system model: Application to toll plaza design. *Transp. Plan. Technol.* **2016**, *39*, 675–692. [CrossRef]
48. Zhang, M.; Ji, S.; Zhou, K. Modelling and application on the extension scale of port based on queuing theory. In Proceedings of the 2010 Ninth International Symposium on Distributed Computing and Applications to Business, Engineering and Science, Hong Kong, China, 10–12 August 2010; pp. 663–666.
49. 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.
50. Lee, J.S.; Kwon, N.; Ham, N.H.; Kim, J.J.; Ahn, Y.H. BIM-based digital fabrication process for a free-form building project in South Korea. *Adv. Civ. Eng.* **2019**, *2019*, 4163625. [CrossRef]
51. Bailey, N.T. A study of queues and appointment systems in hospital out-patient departments, with special reference to waiting-times. *J. R. Stat. Soc. Ser. B (Methodol.)* **1952**, *14*, 185–199. [CrossRef]
52. de Souza, R.M.; Morabito, R.; Chiyoshi, F.Y.; Iannoni, A.P. Incorporating priorities for waiting customers in the hypercube queuing model with application to an emergency medical service system in Brazil. *Eur. J. Oper. Res.* **2015**, *242*, 274–285. [CrossRef]
53. Lin, J.S.; Huang, C.Y.; Fang, C.C. Analysis and assessment of software reliability modeling with preemptive priority queueing policy. *J. Syst. Softw.* **2022**, *187*, 111249. [CrossRef]
54. Kim, C.; Dudin, S.; Taramin, O.; Baek, J. Queueing system MAP | PH | N | N + R with impatient heterogeneous customers as a model of call center. *Appl. Math. Model.* **2013**, *37*, 958–976. [CrossRef]
55. Nan, X.; He, Y.; Guan, L. Queueing model based resource optimization for multimedia cloud. *J. Vis. Commun. Image Represent.* **2014**, *25*, 928–942. [CrossRef]
56. Little, J.D.C. A proof of the queuing formula: L= λW. *Oper. Res.* **1961**, *9*, 383–387. [CrossRef]