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Analysis of the Repair Time of Finishing Works Using a Probabilistic Approach for Efficient Residential Buildings Maintenance Strategies

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Abstract: In general, the long-term maintenance planning of residential buildings is performed based on uniform repair times. However, in fact, various factors, such as the quality and user patterns, affect the performance of residential building components in the Operation and Maintenance (O&M) phase. Hence, various residential building components are repaired at uncertain times, acting as a risk for the residential building maintenance plan. Therefore, an efficient maintenance plan should be established considering maintenance uncertainty. In this regard, this study aims to analyze the uncertainty of repair times for various finishing works in residential buildings based on a probabilistic methodology and outline the implications for the establishment of efficient maintenance strategies in these buildings. Hence, 47,344 repair data for 63 buildings in 12 public residential building complexes completed between 1991 and 2001 in the Republic of Korea were used for analysis. Before the analysis, a repair time matrix was constructed by classifying the finishing works in 25 types and setting service life times to 6–26 years. The repair time distribution for each finishing work was then derived. Results confirmed that basic repair time setting can be performed and various information for reasonable maintenance decision making regarding each finishing work can be provided through a probabilistic approach. The probabilistic approach can be used as a critical decision-making method because there is uncertainty associated with the repair time of each finishing work owing to the performance degradations of various finishing works due to complex causes. Although this study focused on repair time owing to data collection limitations, maintenance strategies with strategic flexibility can be established by developing probabilistic methods that simultaneously consider frequency and cost by securing additional high-quality cost data.

Keywords: residential building; finishing work; repair time distribution; maintenance strategy; Monte-Carlo simulation; uncertainty

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1. Introduction

Sustainability is the goal that endeavors to attain a true balance between the environmental, social, and economic objectives at local, national, regional, and global levels [1]. At the same time that a rigorous debate developed around the concept of environmental sustainability, its definition, indicators and measurements, and its application and realization, it has been proposed that the situation is much less clear concerning social sustainability. Numerous understandings exist as to what comprises social sustainability [2]. Vallance et al. [3] have set forth the idea of three aspects of social sustainability: "development", "bridge", and "maintenance". Especially, "maintenance" refers to the preservation of sociocultural characteristics in the face of change, and the ways in which people actively embrace or resist those changes.

From this point of view, sustainable buildings ensure that buildings and services are in good condition for living, working, and other daily activities. Building maintenance is vital in ensuring the building's sustainability. Maintenance is defined as a combination of actions carried out to retain an item in, or restore it to, an acceptable condition under BS 3811:1984 and ISO 15686-1 (ISO2000) [4,5].

There is a growing awareness on the importance of the maintenance of existing buildings [6–8]. This trend is attributed to the growing complexity of buildings, the increasing proportion of their systems, higher levels of service, and increased maintenance cost proportions with respect to their life-cycle costs. It is strengthened in light of the limited budget commonly allocated to the growing stocks of buildings. These factors place higher demands on life expectancy models that predict the deterioration paths of building components [9]. In South Korea, the proportion of buildings that have deteriorated owing to aging is considerably high. In 2016, the number of buildings older than 30 years was 2,543,217 among a total of 7,043,733 (36%). Recently, public concern regarding the increase of aged buildings has been rising in the country. Correspondingly, the identification of an efficient maintenance strategy has become a pressing matter [10].

Preventive and regular maintenance, repair, and rehabilitation of a building are critical for the maintenance of buildings in a condition in which it continues to satisfactorily fulfill its functions through its operational phase [11]. The management of residential buildings is the art of balancing the demands of numerous stakeholders, the technical constraints of the building's fabric, the growing requirements for the building's environmental performance, and limited budgets. Managers have many degrees-of-freedom in selecting the types of maintenance operations and their timings [12]. This flexibility does not rule out the implementation of measures that are expedient only from a short-term perspective or are limited in meeting the minimum requirements imposed by current standards and regulations. The reactive strategy adopted to achieve the necessary minimum may be cheap but does not help control the functional depreciation of the building. It also exposes users to unnecessarily high future costs. Therefore, there is a call for maintenance planning tools that enable the manager to consider long-term strategies to see beyond the satisfactory technical condition of the building's elements [13].

In general, long-term maintenance planning is established and maintenance budgets are set based on the natural life span of the various parts that make up the respective building [14]. However, residential buildings may fail for a number of reasons, including faulty design, construction, maintenance, materials, and use [15]. Therefore, maintaining buildings costs additional money, although building maintenance can be planned and specified correctly. If the funding available is inadequate, building failure will ultimately ensue [16].

In particular, finishing works are composed of various work types, based on the use of a variety of material types and the construction of multiple parts. Moreover, repairs occur frequently due to various causes, such as construction problems, carelessness of residents during use, and general aging. In addition, the degree of discomfort experienced by occupants is much greater than damage to the structure because repairs have a direct impact on the lives of residents [17]. In this respect, it is extremely important to analyze in detail the uncertainty of potential maintenance schemes, which can generate unexpected maintenance costs in addition to the expected repair time estimated based on long-term maintenance planning for finishing works.

However, the existing literature on finishing works focuses on managing the quality of finishing work in the design and construction process [18–21]. This is indirectly related to the various tasks of the maintenance phase, but there are limitations in managing the quality degradation problem of finishing components generated by various causes in the maintenance phase. Furthermore, research has been conducted on models for the prediction of the repair time of various facilities based on probabilistic concepts [22–25].

The existing literature related to the probabilistic prediction model targeted single components or materials. However, as mentioned above, finishing works are composed of various work types and are associated with a variety of causes for damage; hence, an efficient maintenance plan should be established by considering the uncertainty of maintenance.

In this regard, this study aims to contribute to the establishment of an efficient maintenance strategy for residential buildings based on the analysis of the maintenance uncertainty of various finishing works for residential buildings according to a probabilistic methodology.

2. Background

2.1. Literature Review

Existing studies have mainly focused on environmental sustainability in residential buildings. In other words, various research has been actively conducted on energy-saving technologies such as zero-energy [26–28] and environmental performance evaluation methods such as LCA [29–31].

Pudleiner et al. [26] presented a method to inform the design of Net-Zero Energy buildings through the identification of influential energy efficiency measures. Kaewunruen et al. [27] provided a digital twin model for Net Zero Energy Buildings (NZEB) applications in existing buildings, which applied renewable technologies to the building by aiming to identify ultimate benefit of the building especially in terms of effectiveness and efficiency in energy consumption. Abdou et al. [28] assessed the possibility of achieving net zero energy building in the Moroccan housing stock by combining architectural energy efficiency practices and renewable energies for hot water and electricity productions. Meex et al. [29] investigated possible solutions to apply LCA, including operational energy demand simulation, in early design from two different perspectives: design-oriented user requirements, derived from literature, a survey, interviews, and a focus group with architects; and LCA simplification strategies based on a literature review. Hay et al. [30] proposed an innovative double-skin façade (DSF) system. In this study, mechanical testing of façade elements and a partial life cycle assessment (LCA) focusing on embodied energy and operational energy of a typical functional unit were performed to evaluate mechanical properties and the sustainability performance of the system, respectively. Decorte et al. [31] examined the effect of a one-dimensional approach as simplification strategy on the environmental impact regarding material use and operational energy use for different renovation scenarios applied to a residential high-rise building.

This is because the concept of sustainability basically started with the purpose of limiting fossil fuels to respond to global warming. So, research is being conducted on technologies that can reduce energy such as passive technology, active technology, and management technology in residential buildings.

However, in terms of social sustainability, it is important to secure the quality of life and to maintain the energy performance of residential buildings [2,3,32]. In other words, it is necessary to efficiently manage various building components for maintaining energy performance because of the degradation of buildings over time. In addition, efficient maintenance strategies can extend the life of buildings, leading to waste reduction and resource savings. In this respect, maintenance planning is a critical factor in achieving residential buildings' sustainability [33].

Especially, the maintenance phase for residential buildings requires a systematic maintenance strategy because economic, environmental, and safety problems occur owing to a combination of human and material defects, social and environmental factors, and others. Consequently, advanced building maintenance technologies are required. In this context, studies related to building maintenance plans and decision-making methods have been conducted. Shohet et al. [9] developed a methodology for the establishment of databases listing the deterioration patterns of building components based on their actual conditions. Flores-Colen et al. [15] characterized a systematic methodology for selecting optimal maintenance strategies for façades based on different maintenance policies and interactions with the user. Kim et al. [34] developed a model to minimize fluctuations in the maintenance, repair, and rehabilitation (MR&R) cost profile over the lifecycle of a building based on the adjustment of the execution timing of some MR&R components. Cavalcante et al. [35] proposed a multi-criteria model based on the delay-time concept to provide the builder with a quantitative tool to support the definition of a maintenance-inspection policy. Bucon et al. [14] proposed an optimization model to assist condominium managers in their efforts to define the sequence of maintenance and improvement measures that needed to be executed within a predefined planning horizon to achieve predefined levels of building performance. These studies searched for building maintenance measures from various perspectives. In particular, it is commonly mentioned in these studies that the building repair time is one of the most important considerations for effective maintenance.

So, many studies have attempted to derive a reasonable repair time for various building components. Alani et al. [36] presented a comparative study of three well-established building maintenance forecasting models in conjunction with a quantitative model. Tirpude et al. [37] proposed an innovative model to achieve urgent repairs using the information obtained through various condition assessment techniques and utilized a consistent repair priority scale to categorize various types of condition assessment data. Park et al. [38] proposed a case-based reasoning-based model to estimate the time at which the first repair was needed after the completion of construction, even in phases in which maintenance-related information was scarce. Kwon et al. [39] developed a model for the prediction of the repair time for the building type based on the application of a genetic algorithm, multiple linear regression analysis, feature counting method, and fuzzy analytical hierarchy process to case-based reasoning. However, these studies only targeted specific building components or had limitations associated with various uncertainties during the building maintenance phase.

In particular, studies have applied probabilistic models to reflect the uncertainty caused by various factors during the maintenance period. Kliukas et al. [22] presented new probability-based approaches for predicting the durability of deteriorating existing building elements with their service and proof action effects with greater accuracy, and other statistical data from local or field investigations. Kim et al. [23] presented a probabilistic approach to establish optimum inspection/repair planning for deteriorating structures. Kim et al. [24] proposed a generalized probabilistic framework for optimum inspection and maintenance planning of deteriorating structures. Silva et al. [25] focused on a probabilistic analysis of the degradation conditions of render facades and their relationship with the most influential environmental factors. However, they mostly considered the durability of concrete structures, such as bridges. Further, studies targeting buildings have proposed mathematical models, but they have limitations in analyzing systematic and detailed repair time patterns for various building components.

A review of the existing literature related to finishing works showed that most studies searched for measures to improve the quality of finishing work in the design and construction phases in consideration of the complexity and diversity of finishing works. Manrique et al. [18] focused on the procedure utilized in the construction of tilt-up irregular concrete panels constructed onsite using concrete slabs and wooden formwork. Brodetskaia et al. [19] explored the nature of finishing work flows and sought to test the proposal that product unit cycle times, labor productivity, and project durations in the finishing works of building construction can be improved by implementing pull-flow control at the level of individual production operations. Belmonte et al. [20] validated an image analysis process (QSI) to evaluate the surface quality of self-compacting concrete that can be affected by trapped air holes in addition to other surface defects. Yoon et al. [21] proposed the design, construction, and curing integrated management of defects in the finishing works of apartment buildings. This study showed that the proposed management method can be used as a basis for defect prevention measures for high-quality finishing work. Such improvement in the quality of finishing works in the design and construction phases has a positive effect on the maintenance of finishing components. However, existing studies have discovered that there is a limitation in finding measures to effectively maintain the performance of finishing components owing to various influencing factors in the maintenance phase.

Accordingly, this study aims to analyze repair-time patterns reflecting uncertainty beyond the limits of fixed repair time or inspection plans for the finishing works of residential buildings.

2.2. Monte Carlo Simulation

This study used a Monte Carlo simulation to analyze the repair data based on a probabilistic approach. Subjective evaluations are rarely quantified precisely, as deliberate or unintended bias can always be present in such evaluations. A way to deal with bias is to build a model describing the ongoing process, followed by running a Monte Carlo simulation to reproduce it. This procedure can be varied by eliminating evaluators or by changing the weights of the criteria to account for biases. Statistical sampling began in the early 1900s. It has thus been in existence before the invention of the Monte Carlo method. However, this method used for the first time a computer to automate sampling. The Monte Carlo method was employed to approximate solutions to quantitative problems. The method transforms a deterministic model in which the equation yields one output based on the original input parameters to a stochastic one. One of the major benefits of the Monte Carlo method is that, in contrast to deterministic models, it can generate random variables to evaluate a decision problem from many angles. Replicating or modeling real systems to predict a specific behavior and investigate thousands of different scenarios for the same case reveal the system's sensitivity to random input variations, lack of knowledge, or input error. Understanding this sensitivity facilitates decision making [40].

The method transforms a deterministic model, in which the equation gives one output based on the original input parameters, into a stochastic one. The latter model randomly generates input variables from probability distributions that sample a certain population and in which the output is different for every run of the model. The off-the-shelf software simulates the model many times, taking for each iteration a different point from the specified probability distribution for every input. The calculated output will also be different for every run, and its distribution will be calculated. This assures the owner that the importance factors were not the only aspect of the analysis driving the results.

Performing a Monte Carlo simulation involves three steps:

- Step 1, an equation for simulation is developed.
- Step 2, the evaluation data are inputted, and the probability distribution that fits the data set is identified to generate random inputs.
- Step 3, several iterations are performed to evaluate the model. The number of iterations should allow the output's convergence to be satisfactory for the analysis.

One of the major benefits of the Monte Carlo method is that, in contrast to deterministic models, it can generate random variables in order to look at a decision problem from many angles. As a result, the Monte Carlo method can minimize the bias of repair data because it generates random inputs by adjusting the probability distribution fitted to the actual repair data. Furthermore, because the likelihood of repair at a given time can be effectively identified by analyzing the probabilistic patterns of repair time using the Monte Carlo method, it is possible to solve the problems of the existing uniform repair time and establish an efficient performance-oriented maintenance strategy.

3. Theoretical Framework

Various repairs are performed to maintain the performance of residential buildings through long-term maintenance plans. As shown in Figure 1, the repair times specified in the long-term maintenance plan were fixed based on category. Thus, given that the repair cost can be expected, the maintenance costs of public residential buildings are regularly earmarked and used for the expected repair time. However, because of the nature of public residential buildings that are used for a long period of time, many unexpected repairs are requires owing to various causes. In particular, immediate responses are essential for building finishing which affect the performance and beauty of buildings because they can be directly checked with the naked eye and have a significant effect on the residents' lives. Therefore, it is crucial to establish an efficient maintenance strategy by effectively analyzing the patterns of unexpected repairs. In this respect, the present study aims to probabilistically analyze unexpected repair data among all repair cases and identify measures in response to uncertainties associated with repairs in the maintenance phase.

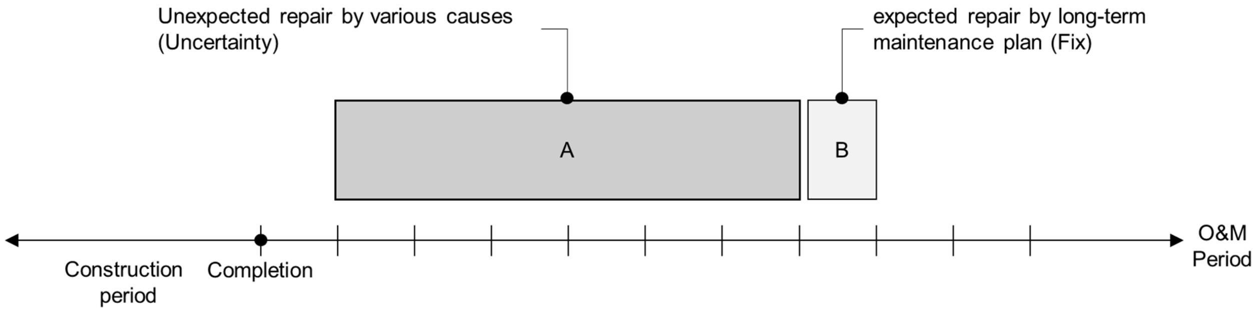

Figure 1. Uncertainty of repair in the O&M phase.

To derive a repair time pattern which reflects uncertainty using the repair frequency data by the time of finishing work for residential buildings, this study was conducted in four steps, as shown in Figure 2.

The first step is data collection. This paper examined the repair histories of 65 residential buildings in 12 public residential building complexes completed in the Republic of Korea between 1991 and 2001. The data detailed the repair times and repaired finishing work type for 65 buildings. As a result, this study collected 47,344 repair data to verify repair times and finishing work types.

The second step is to set the repair time matrix. For this step, the finishing works were classified based on the investigation of 47,344 repair data and previous studies. Moreover, repair times were identified through data review. The repair time matrix was set through repair times and finishing work types. The repair time matrix serves as a framework for allocating repair data to each cell that is categorized based on repair time and finishing work and for generating a repair frequency distribution for each cell.

The third step is to allocate repair data to each cell in the repair time matrix. In this paper, repair frequency is defined at the building-level. As 47,344 repair data are distributed to 65 buildings, the repair data allocated to the repair time matrix are the building-level repair frequencies that correspond to the conditions of the repair time and finishing work for each cell.

The fourth step is to define the repair frequency distributions for each cell based on the building-level repair data allocated to each cell. In this study, the repair frequency distributions of each cell were determined by performing the chi-square test as a goodness-of-fit test among the five discrete distributions such as negative binomial, Poisson, geometric, binomial, and uniform distributions [41].

Finally, a Monte Carlo simulation was performed for the repair frequency distribution for each cell of finishing works based on Equation (1) below. Equation (1) expresses the weighted average of the repair frequency based on the year of the finishing work. The difference from the existing method is that it derives a probability distribution that combines a number of different cases by performing Monte Carlo simulations after entering the repair frequency distribution derived above, instead of entering each variable as a single value. By using the repair time distribution of each finishing work, it is possible to identify the degree of uncertainty. This will contribute to the establishment of maintenance strategies that effectively respond to uncertainty, moving beyond the limitations of the conventional method that simply sets the repair time.

$$DRT_n = \frac{\sum\left(D_{(t,n)} \times T_t\right)}{\sum D_{(t,n)}} \quad (1)$$

$DRT_n = W_n$ finishing works' repair time distribution.
$D_{(t,n)} = W_n$ finishing works' frequency distribution at time t.
T_t = repair time t.

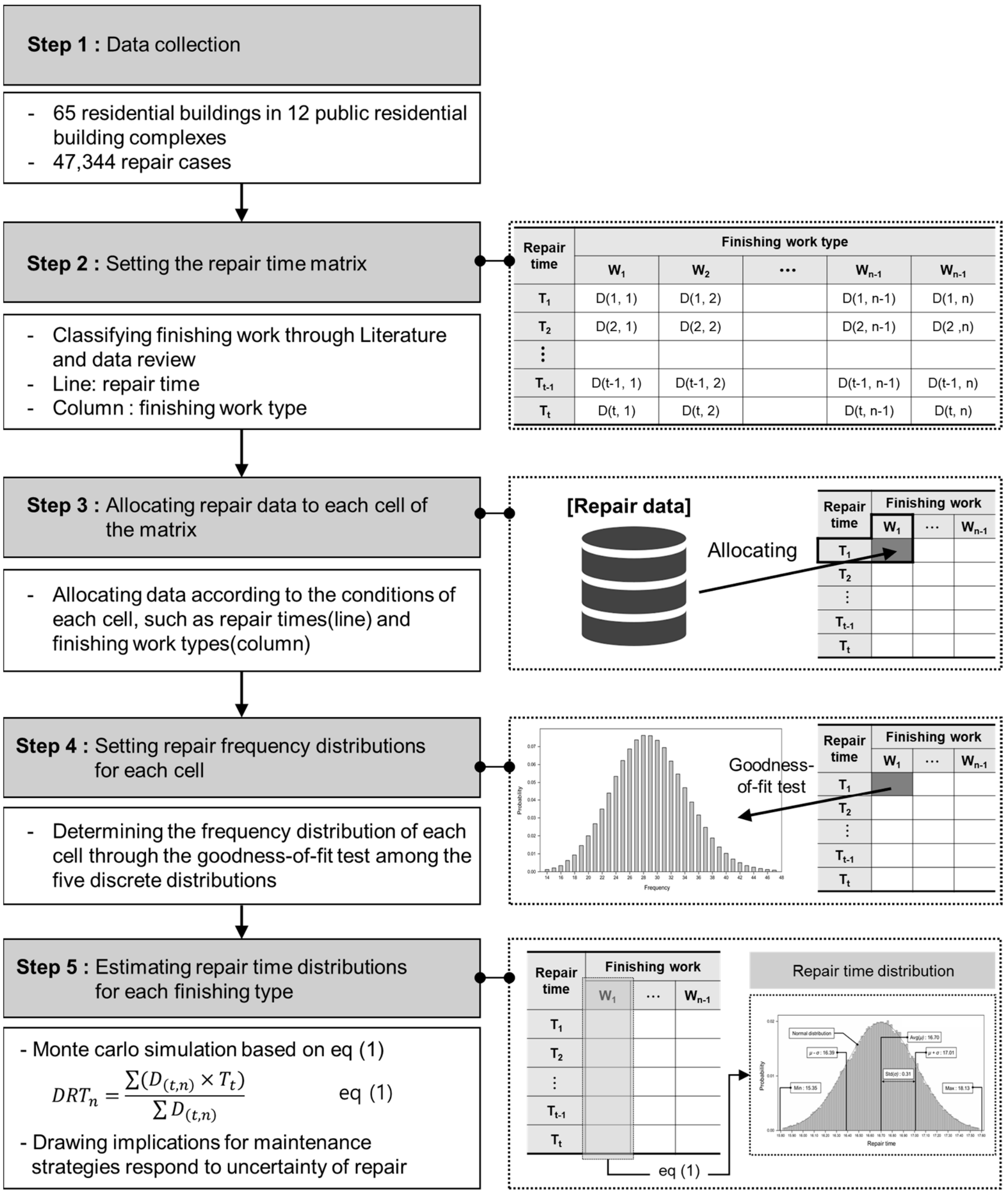

Figure 2. Research flow of the proposed methodology.

4. Results

4.1. Data Collection and Setting the Repair Time Matrix

In this study, the repair times of 65 residential buildings in 12 public residential building complexes completed between 1991 and 2001 in the Republic of Korea were analyzed using a probabilistic approach as shown in Table 1. Because there are various types of finishing work, the existing literature was examined, as shown in Table 2, to investigate the scope of the analysis. The types of finishing works were classified in nine types as follows: interior (I), doors and windows (DW), painting (P), tiling (T), front door (FD), furniture (F), waterproofing (W), plastering (PL), and carpentry (CA). The types of finishing works can be subdivided based on the work type in materials, locations, components, and other types. Thus, in this study, the nine work types were further subdivided in 25 types using the repair data of public residential buildings based on the cases listed in Table 1. As it can be observed from Table 3, I was divided in three types, DW in five types, P in three types, T in two types, FD in three types, F in two types, and W in four types. PL and CA were not subdivided because the classification criteria for the data were not clear.

Table 1. Overview of public residential buildings.

Complex	Number of Buildings	Year Completed (Year)	Total Floor Area (m^2)	Number of Households
A	5	2000	52,434	598
B	3	2001	12,678	191
C	4	2000	48,000	510
D	4	2000	49,084	698
E	4	2001	43,508	500
F	5	1997	47,208	660
G	8	1996	69,017	1432
H	2	1996	19,850	335
I	8	1991	73,357	1623
J	4	1994	45,092	1000
K	7	1991	84,189	1807
L	11	1991	125,080	2619

Table 2. Finishing work classifications.

Classification	Researcher					
	Yoon et al. [21]	Warszawski et al. [42]	Chong et al. [43]	Forcada et al. [44]	Rotimi et al [45]	Rho et al. [46]
interior (I)	O	O			O	O
doors and windows (DW)	O		O	O	O	
painting (P)	O	O	O	O	O	O
tiling (T)	O	O	O	O	O	O
front door (FD)					O	O
furniture (F)	O			O		
waterproofing (W)			O		O	O
plastering (PL)		O	O		O	O
carpentry (CA)						O

Table 3. Detailed classifications of finishing work.

Classification	Subcategory
interior (I)	wall (I1), floor (I2), ceiling (I3), molding (I4)
doors and windows (DW)	wood (DW1), steel (DW2), plastic (DW3), aluminum (DW4), window screen (DW5)
painting (P)	water paint (P1), oil paint (P2), anti-sweating paint (P3)
tiling (T)	wall (T1), floor (T2)
front door (FD)	body (FD1), doorframe (FD2), components (FD3)
furniture (F)	general (F1), kitchen (F2)
waterproofing (W)	membrane waterproofing (W1), liquid waterproofing cement (W2), sheet waterproofing (W3), caulking (W4)
plastering (PL)	-
carpentry (CA)	-

The repair time dataset used in this study was based on actual repair cases investigated between 2007 and 2017 for the 65 residential buildings in 12 public residential building complexes listed in Table 1. So, the time of repairs in this dataset ranged from 7 to 26 years since the completion of construction, and the repair times were set accordingly. Based on the finishing work and repair time, the repair time matrix is defined as shown in Table 4. In addition, the frequency distribution for each cell of the matrix was set based on the repair cases of public residential buildings.

Table 4. Repair time matrix.

Repair Time (Year)	Finishing Work											
	I				DW					P		
	1	2	3	4	1	2	3	4	5	1	2	3
7	D(1,1)	D(1,2)	D(1,3)	D(1,4)	D(1,5)	D(1,6)	D(1,7)	D(1,8)	D(1,9)	D(1,10)	D(1,11)	D(1,12)
8	D(2,1)	D(2,2)	D(2,3)	D(2,4)	D(2,5)	D(2,6)	D(2,7)	D(2,8)	D(2,9)	D(2,10)	D(2,11)	D(2,12)
9	D(3,1)	D(3,2)	D(3,3)	D(3,4)	D(3,5)	D(3,6)	D(3,7)	D(3,8)	D(3,9)	D(3,10)	D(3,11)	D(3,12)
10	D(4,1)	D(4,2)	D(4,3)	D(4,4)	D(4,5)	D(4,6)	D(4,7)	D(4,8)	D(4,9)	D(4,10)	D(4,11)	D(4,12)
11	D(5,1)	D(5,2)	D(5,3)	D(5,4)	D(5,5)	D(5,6)	D(5,7)	D(5,8)	D(5,9)	D(5,10)	D(5,11)	D(5,12)
12	D(6,1)	D(6,2)	D(6,3)	D(6,4)	D(6,5)	D(6,6)	D(6,7)	D(6,8)	D(6,9)	D(6,10)	D(6,11)	D(6,12)
13	D(7,1)	D(7,2)	D(7,3)	D(7,4)	D(7,5)	D(7,6)	D(7,7)	D(7,8)	D(7,9)	D(7,10)	D(7,11)	D(7,12)
14	D(8,1)	D(8,2)	D(8,3)	D(8,4)	D(8,5)	D(8,6)	D(8,7)	D(8,8)	D(8,9)	D(8,10)	D(8,11)	D(8,12)
15	D(9,1)	D(9,2)	D(9,3)	D(9,4)	D(9,5)	D(9,6)	D(9,7)	D(9,8)	D(9,9)	D(9,10)	D(9,11)	D(9,12)
16	D(10,1)	D(10,2)	D(10,3)	D(10,4)	D(10,5)	D(10,6)	D(10,7)	D(10,8)	D(10,9)	D(10,10)	D(10,11)	D(10,12)
17	D(11,1)	D(11,2)	D(11,3)	D(11,4)	D(11,5)	D(11,6)	D(11,7)	D(11,8)	D(11,9)	D(11,10)	D(11,11)	D(11,12)
18	D(12,1)	D(21,2)	D(12,3)	D(12,4)	D(12,5)	D(12,6)	D(12,7)	D(12,8)	D(12,9)	D(12,10)	D(12,11)	D(12,12)
19	D(13,1)	D(13,2)	D(13,3)	D(13,4)	D(13,5)	D(13,6)	D(13,7)	D(13,8)	D(13,9)	D(13,10)	D(13,11)	D(13,12)
20	D(14,1)	D(14,2)	D(14,3)	D(14,4)	D(14,5)	D(14,6)	D(14,7)	D(14,8)	D(14,9)	D(14,10)	D(14,11)	D(14,12)
21	D(15,1)	D(15,2)	D(15,3)	D(15,4)	D(15,5)	D(15,6)	D(15,7)	D(15,8)	D(15,9)	D(15,10)	D(15,11)	D(15,12)
22	D(16,1)	D(16,2)	D(16,3)	D(16,4)	D(16,5)	D(16,6)	D(16,7)	D(16,8)	D(16,9)	D(16,10)	D(16,11)	D(16,12)
23	D(17,1)	D(17,2)	D(17,3)	D(17,4)	D(17,5)	D(17,6)	D(17,7)	D(17,8)	D(17,9)	D(17,10)	D(17,11)	D(17,12)
24	D(18,1)	D(18,2)	D(18,3)	D(18,4)	D(18,5)	D(18,6)	D(18,7)	D(18,8)	D(18,9)	D(18,10)	D(18,11)	D(18,12)
25	D(19,1)	D(19,2)	D(19,3)	D(19,4)	D(19,5)	D(19,6)	D(19,7)	D(19,8)	D(19,9)	D(19,10)	D(19,11)	D(19,12)
26	D(20,1)	D(20,2)	D(20,3)	D(20,4)	D(20,5)	D(20,6)	D(20,7)	D(20,8)	D(20,9)	D(20,10)	D(20,11)	D(20,12)

Repair Time (Year)	Finishing Work												
	T		FD			F		W				PL	CA
	1	2	1	2	3	1	2	1	2	3	4		
7	D(1,13)	D(1,14)	D(1,15)	D(1,16)	D(1,17)	D(1,18)	D(1,19)	D(1,20)	D(1,21)	D(1,22)	D(1,23)	D(1,24)	D(1,25)
8	D(2,13)	D(2,14)	D(2,15)	D(2,16)	D(2,17)	D(2,18)	D(2,19)	D(2,20)	D(2,21)	D(2,22)	D(2,23)	D(2,24)	D(2,25)
9	D(3,13)	D(3,14)	D(3,15)	D(3,16)	D(3,17)	D(3,18)	D(3,19)	D(3,20)	D(3,21)	D(3,22)	D(3,23)	D(3,24)	D(3,25)
10	D(4,13)	D(4,14)	D(4,15)	D(4,16)	D(4,17)	D(4,18)	D(4,19)	D(4,20)	D(4,21)	D(4,22)	D(4,23)	D(4,24)	D(4,25)
11	D(5,13)	D(5,14)	D(5,15)	D(5,16)	D(5,17)	D(5,18)	D(5,19)	D(5,20)	D(5,21)	D(5,22)	D(5,23)	D(5,24)	D(5,25)
12	D(6,13)	D(6,14)	D(6,15)	D(6,16)	D(6,17)	D(6,18)	D(6,19)	D(6,20)	D(6,21)	D(6,22)	D(6,23)	D(6,24)	D(6,25)
13	D(7,13)	D(7,14)	D(7,15)	D(7,16)	D(7,17)	D(7,18)	D(7,19)	D(7,20)	D(7,21)	D(7,22)	D(7,23)	D(7,24)	D(7,25)
14	D(8,13)	D(8,14)	D(8,15)	D(8,16)	D(8,17)	D(8,18)	D(8,19)	D(8,20)	D(8,21)	D(8,22)	D(8,23)	D(8,24)	D(8,25)
15	D(9,13)	D(9,14)	D(9,15)	D(9,16)	D(9,17)	D(9,18)	D(9,19)	D(9,20)	D(9,21)	D(9,22)	D(9,23)	D(9,24)	D(9,25)
16	D(10,13)	D(10,14)	D(10,15)	D(10,16)	D(10,17)	D(10,18)	D(10,19)	D(10,20)	D(10,21)	D(10,22)	D(10,23)	D(10,24)	D(10,25)
17	D(11,13)	D(11,14)	D(11,15)	D(11,16)	D(11,17)	D(11,18)	D(11,19)	D(11,20)	D(11,21)	D(11,22)	D(11,23)	D(11,24)	D(11,25)
18	D(12,13)	D(12,14)	D(12,15)	D(12,16)	D(12,17)	D(12,18)	D(12,19)	D(12,20)	D(12,21)	D(12,22)	D(12,23)	D(12,24)	D(12,25)
19	D(13,13)	D(13,14)	D(13,15)	D(13,16)	D(13,17)	D(13,18)	D(13,19)	D(13,20)	D(13,21)	D(13,22)	D(13,23)	D(13,24)	D(13,25)
20	D(14,13)	D(14,14)	D(14,15)	D(14,16)	D(14,17)	D(14,18)	D(14,19)	D(14,20)	D(14,21)	D(14,22)	D(14,23)	D(14,24)	D(14,25)
21	D(15,13)	D(15,14)	D(15,15)	D(15,16)	D(15,17)	D(15,18)	D(15,19)	D(15,20)	D(15,21)	D(15,22)	D(15,23)	D(15,24)	D(15,25)
22	D(16,13)	D(16,14)	D(16,15)	D(16,16)	D(16,17)	D(16,18)	D(16,19)	D(16,20)	D(16,21)	D(16,22)	D(16,23)	D(16,24)	D(16,25)
23	D(17,13)	D(17,14)	D(17,15)	D(17,16)	D(17,17)	D(17,18)	D(17,19)	D(17,20)	D(17,21)	D(17,22)	D(17,23)	D(17,24)	D(17,25)
24	D(18,13)	D(18,14)	D(18,15)	D(18,16)	D(18,17)	D(18,18)	D(18,19)	D(18,20)	D(18,21)	D(18,22)	D(18,23)	D(18,24)	D(18,25)
25	D(19,13)	D(19,14)	D(19,15)	D(19,16)	D(19,17)	D(19,18)	D(19,19)	D(19,20)	D(19,21)	D(19,22)	D(19,23)	D(19,24)	D(19,25)
26	D(20,13)	D(20,14)	D(20,15)	D(20,16)	D(20,17)	D(20,18)	D(20,19)	D(20,20)	D(20,21)	D(20,22)	D(20,23)	D(20,24)	D(20,25)

Note: I1 = Interior: wall; I2 = Interior: floor; I3 = Interior: ceiling; I4 = Interior: molding; DW1 = Door and window: wood; DW2 = Door and window: steel; DW3 = Door and window: plastic; DW4 = Door and window: Aluminum; DW5 = Door and window: window screen; P1 = Painting: water paint; P2 = Painting: oil paint; P3 = Painting: anti-sweating paint; T1 = Tiling: wall; T2 = Tiling: floor; FD1 = Front door: body; FD2 = Front door: doorframe; FD3 = Front door: components; F1 = Furniture: general; F2 = Furniture: kitchen; W1 = Waterproofing: membrane waterproofing; W2 = Waterproofing: liquid waterproofing cement; W3 = Waterproofing: sheet waterproofing; W4 = Waterproofing: caulking; PL = Plastering; CA = Carpentry.

In this study, 47,344 repair cases performed for 20 years for 63 buildings in 12 public residential building complexes in South Korea were investigated and distributed to the above matrix. Repair cases conducted according to a long-term maintenance plan were excluded from the analysis. As mentioned above, the repair costs for repair cases performed according to a long-term maintenance plan were earmarked because they were planned based on the expected repair times. In other words, sufficient responses are possible for these expected costs because uncertainty is eliminated. This study focuses on the generation of unexpected costs and aims to improve the uncertainty of long-term maintenance plans by analyzing the repair data of cases that generate such additional costs. Hence, the 47,344 repair cases analyzed in this study were those in which unexpected costs were generated.

The repair data in Table 5 show that the repair frequency of interior work accounts for a high share of approximately 40.4% of all repairs. In particular, the interior wall (I1) and interior floor (I2) required a high frequency of repairs with 12,406 cases (25.4%) and 5991 cases (12.7%), respectively. These correspond to the finishing of the outermost parts of components, such as walls and floors comprising the spaces, which can age the fastest and are highly likely to be damaged owing to the occupants' carelessness during use. Furthermore, there were 3965 repair cases (8.4%) for doors and plastic windows (DW3), and 1885 repair cases (4.0%) for the front door-body (FD1). These repairs were mostly caused by operational problems due to the nature of the components. Damage cases due to various causes, such as misconstruction, material properties, and construction area, were found, including 3443 cases (7.3%) for water paint (P1), 3914 cases (8.3%) for kitchen furniture (F2), 2967 cases (6.3%) for wall tiling (T1), and 2214 cases (4.7%) for waterproofing liquid cement (W2).

Table 5. Repair data in public residential buildings.

Classification	Subcategory	Case
interior (I)	wall (I1)	12,406 (25.4%)
	floor (I2)	5991 (12.7%)
	ceiling (I3)	972 (2.1%)
	molding (I4)	95 (0.2%)
doors and windows (DW)	wood (DW1)	1997 (4.2%)
	steel (DW2)	163 (0.3%)
	plastic (DW3)	3965 (8.4%)
	aluminum (DW4)	196 (0.4%)
	window screen (DW5)	1049 (2.2%)
painting (P)	water paint (P1)	3443 (7.3%)
	oil paint (P2)	1006 (2.1%)
	anti-sweating paint (P3)	300 (0.6%)
tiling (T)	wall (T1)	2967 (6.3%)
	floor (T2)	1482 (3.1%)
front door (FD)	body (FD1)	1885 (4.0%)
	doorframe (FD2)	710 (1.5%)
	components (FD3)	1006 (2.1%)
furniture (F)	general (F1)	292 (0.6%)
	kitchen (F2)	3914 (8.3%)
waterproofing (W)	membrane waterproofing (W1)	116 (0.2%)
	liquid waterproofing cement (W2)	2214 (4.7%)
	sheet waterproofing (W3)	78 (0.2%)
	caulking (W4)	794 (1.7%)
plastering (PL)	-	349 (0.7%)
carpentry (CA)	-	314 (0.7%)
Total		47,344 (100.0%)

Table 6 shows the allocation of the repair data for each finishing work identified in Table 5 to the repair time matrix in Table 4. As shown in Table 6, the repair data for each finishing work are arranged according to repair time. In other words, the repair data was allocated based on the repair time and finishing work conditions and reconfigured as building-level repair data. The repair frequency distribution for each cell is generated based on building-level repair data that meet the conditions of each cell. Furthermore, the empty cells in Table 6 indicate that the corresponding finishing work of 65 buildings was not repaired at the time. It was defined as zero in this case without generating a probability distribution.

Table 6. Datasets allocated to each cell of the repair time matrix.

Repair Time (Year)	Finishing Work																								
	I				DW					P			T		FD			F		W				PL	CA
	1	2	3	4	1	2	3	4	5	1	2	3	1	2	1	2	3	1	2	1	2	3	4		
7	162	163	-	1	-	-	3	-	-	16	-	-	10	2	-	-	-	-	6	1	2	-	2	-	-
8	816	799	17	1	25	-	17	3	6	57	9	-	34	9	5	2	4	-	87	5	28	-	7	1	-
9	297	245	5	-	54	4	688	10	10	95	56	-	52	19	15	9	14	8	152	5	15	1	15	1	4
10	642	564	11	-	29	1	42	8	8	122	49	1	79	20	19	10	15	24	196	2	19	1	14	3	13
11	269	191	2	5	8	-	18	1	6	106	60	-	98	32	11	1	6	9	107	6	39	1	26	-	24
12	412	210	17	-	32	12	1734	9	8	146	99	-	119	28	28	6	39	9	165	9	19	-	10	8	30
13	575	334	23	7	54	9	64	6	16	305	106	-	210	59	58	12	45	14	124	6	50	3	18	8	25
14	477	414	26	5	30	3	67	3	10	155	88	5	259	44	46	1	40	2	98	2	69	-	23	1	1
15	386	199	34	2	38	16	72	14	11	112	70	1	597	31	74	3	47	8	293	5	67	8	13	6	4
16	1564	821	47	8	98	15	130	11	121	165	34	1	271	63	85	8	46	30	212	3	89	4	13	15	6
17	530	195	50	5	87	11	132	19	85	129	11	2	253	87	60	9	45	12	66	17	146	7	36	12	8
18	555	304	94	4	201	19	142	39	123	183	51	1	164	174	213	167	200	32	109	8	187	17	42	36	25
19	774	398	115	3	263	18	187	27	93	219	59	1	164	150	322	249	175	20	196	8	247	13	58	28	27
20	889	218	95	10	191	17	198	15	122	301	50	3	141	176	130	92	57	21	408	2	193	3	35	17	21
21	547	227	95	10	193	4	106	12	81	262	42	28	133	127	93	28	45	18	143	4	268	7	78	41	10
22	730	145	92	8	175	3	105	3	71	286	123	61	80	147	115	63	33	9	328	2	231	4	86	60	18
23	1103	254	115	8	235	5	128	2	83	478	30	94	95	109	187	11	13	21	383	16	267	5	173	69	67
24	714	147	65	8	138	5	65	7	90	168	44	17	95	85	157	25	58	34	394	8	84	-	51	20	26
25	347	105	44	6	64	2	47	6	59	76	14	18	57	53	146	10	71	14	277	3	77	2	45	17	2
26	257	58	25	4	82	19	20	1	46	62	11	67	56	67	121	4	53	7	170	4	117	2	49	6	3
Total	12,046	5991	972	95	1997	163	3965	196	1049	3443	1006	300	2967	1482	1885	710	1006	292	3914	116	2214	78	794	349	314

4.2. Setting Repair Frequency Distributions for Each Cell

This paper derived the repair frequency distribution of each cell based on the corresponding building-level repair data allocated to the repair time matrix. As shown in Table 7, the goodness-of-fit test of five representative discrete distributions was performed on the building-level repair data allocated to each cell. Table 7 shows the repair frequency distribution for each cell based on a chi-square test, which is one of the goodness-of-fit tests.

Table 7. Results of chi-square test for repair frequency distributions.

Repair Time (Year)	Finishing Work											
	I				DW					P		
	1	2	3	4	1	2	3	4	5	1	2	3
7	Bi(11.45)	Bi(13.03)	-	Po(0.000)	-	-	Po(0.000)	-	-	Po(12.98)	-	-
8	Nb(0.173)	Nb(0.170)	Po(8.504)	Po(0.000)	Bi(0.690)	-	Po(2.434)	Po(0.000)	Po(2.639)	Nb(0.231)	Po(2.282)	-
9	Nb(0.030)	Po(0.800)	Po(0.000)	-	Ge(0.075)	Po(0.000)	Ge(17.87)	Po(0.158)	Po(0.732)	Nb(0.309)	Ge(8.895)	-
10	Nb(0.452)	Ge(4.849)	Po(0.141)	-	Po(0.870)	Po(0.000)	Ge(1.615)	Po(0.144)	Po(1.630)	Ge(6.176)	Ge(4.300)	Po(0.000)
11	Ge(3.499)	Nb(5.012)	Po(0.000)	Po(0.000)	Po(0.233)	-	Po(1.122)	Po(0.000)	Po(1.361)	Ge(3.224)	Ge(12.07)	-
12	Ge(5.090)	Nb(4.244)	Po(3.606)	-	Po(9.308)	Po(5.261)	Ge(77.97)	Po(2.525)	Po(0.233)	Ge(19.59)	Ge(26.53)	-
13	Ge(1.070)	Ge(6.615)	Po(1.183)	Po(0.370)	Bi(1.401)	Po(0.650)	Ge(3.254)	Po(0.066)	Po(0.145)	Ge(10.44)	Ge(26.55)	-
14	Ge(8.208)	Ge(5.880)	Po(6.283)	Po(0.000)	Po(6.989)	Po(0.000)	Ge(8.216)	Po(0.000)	Po(0.005)	Nb(2.082)	Ge(8.912)	Po(0.000)
15	Ge(2.878)	Nb(5.071)	Po(9.432)	Po(0.000)	Bi(0.113)	Po(3.016)	Ge(5.271)	Po(0.929)	Po(1.778)	Ge(2.400)	Ge(11.96)	Po(0.000)
16	Ge(21.50)	Ge(77.24)	Po(20.21)	Po(0.030)	Ge(8.956)	Po(1.692)	Ge(9.122)	Po(0.469)	Ge(19.43)	Ge(18.78)	Po(16.70)	Po(0.000)
17	Ge(20.69)	Ge(14.05)	Po(17.00)	Po(0.000)	Ge(7.837)	Po(0.112)	Ge(14.70)	Po(3.214)	Ge(17.55)	Ge(12.41)	Po(1.924)	Po(0.000)
18	Nb(2.116)	Ge(2.360)	Ge(8.500)	Po(0.000)	Ge(1.966)	Po(1.992)	Ge(3.702)	Po(8.586)	Ge(4.171)	Nb(4.174)	Ge(12.71)	Po(0.000)
19	Nb(2.579)	Ge(10.97)	Ge(12.25)	Po(0.000)	Nb(5.954)	Po(1.007)	Nb(1.370)	Po(4.694)	Ge(5.209)	Ge(1.155)	Ge(0.215)	Po(0.000)
20	Ge(1.815)	Ge(3.912)	Ge(18.57)	Po(0.130)	Ge(6.990)	Po(3.908)	Nb(3.754)	Po(3.625)	Ge(6.290)	Nb(11.89)	Ge(0.000)	Po(0.000)
21	Nb(10.60)	Ge(9.964)	Ge(4.801)	Po(1.177)	Nb(5.482)	Po(0.000)	Ge(1.804)	Po(1.476)	Ge(12.04)	Ge(31.39)	Ge(0.000)	Po(7.835)
22	Nb(2.917)	Nb(0.445)	Ge(0.952)	Po(0.760)	Nb(0.047)	Po(0.000)	Nb(1.160)	Po(0.000)	Ge(0.973)	Nb(2.406)	Ge(20.92)	Ge(2.392)
23	Nb(7.984)	Ge(8.744)	Ge(5.622)	Po(0.194)	Ge(1.012)	Po(0.000)	Ge(4.828)	Po(0.000)	Ge(1.226)	Nb(9.062)	Po(12.23)	Ge(15.28)
24	Nb(0.899)	Ge(2.299)	Ge(2.942)	Po(0.703)	Ge(2.137)	Po(0.000)	Ge(1.180)	Po(0.974)	Ge(5.868)	Ge(12.24)	Ge(0.426)	Po(3.091)
25	Nb(7.990)	Ge(7.282)	Po(4.838)	Po(0.030)	Bi(0.868)	Po(0.000)	Po(1.733)	Po(0.097)	Ge(5.872)	Ge(3.424)	Po(2.316)	Po(0.609)
26	Ge(0.968)	Ge(0.477)	Po(4.223)	Po(0.000)	Ge(6.770)	Po(0.036)	Po(0.590)	Po(0.000)	Ge(0.266)	Nb(0.966)	Po(0.660)	Ge(10.96)

Repair Time (Year)	Finishing Work											
	T		FD			F		W				PL	CA
	1	2	1	2	3	1	2	1	2	3	4		
7	Po(3.137)	Po(0.000)	-	-	-	-	Po(1.242)	Po(0.000)	Po(0.000)	-	Po(0.000)	-	-
8	Ge(0.315)	Po(3.904)	Po(0.000)	Po(0.000)	Po(0.000)	-	Ge(1.480)	Po(0.000)	Ge(1.805)	-	Po(0.197)	Po(0.000)	-
9	Ge(5.951)	Po(1.082)	Po(1.307)	Po(0.337)	Po(0.856)	Po(0.575)	Po(3.325)	Po(0.000)	Po(2.532)	Po(0.000)	Po(2.532)	Po(0.000)	Po(0.000)
10	Ge(18.77)	Po(5.376)	Po(1.759)	Po(0.279)	Po(0.265)	Po(15.14)	Ge(10.18)	Po(0.000)	Po(4.528)	Po(0.000)	Po(1.208)	Po(0.000)	Po(2.840)
11	Ge(21.39)	Po(10.67)	Po(0.300)	Po(0.000)	Po(0.493)	Po(0.611)	Ge(9.059)	Po(2.658)	Po(12.39)	Po(0.000)	Po(8.121)	-	Po(16.06)
12	Ge(27.80)	Po(6.878)	Po(6.878)	Po(0.051)	Ge(0.000)	Po(0.611)	Ge(10.65)	Po(0.611)	Po(0.324)	-	Po(0.075)	Po(0.814)	Po(18.16)
13	Ge(13.25)	Ge(0.564)	Ge(0.576)	Po(0.715)	Po(6.465)	Po(0.378)	Nb(6.538)	Po(1.376)	Po(8.644)	Po(0.000)	Po(2.148)	Po(0.846)	Po(20.37)
14	Ge(18.28)	Ge(0.000)	Ge(1.867)	Po(0.000)	Po(1.949)	Po(0.000)	Ge(1.866)	Po(0.000)	Ge(10.23)	-	Po(4.219)	Po(0.000)	Po(0.000)
15	Ge(45.94)	Po(14.76)	Ge(4.516)	Po(0.000)	Po(5.089)	Po(0.258)	Ge(13.18)	Po(0.000)	Ge(3.204)	Po(0.846)	Po(0.000)	Po(0.040)	Po(0.000)
16	Ge(39.12)	Ge(8.028)	Ge(16.25)	Po(0.030)	Po(9.483)	Po(13.05)	Ge(38.42)	Po(0.000)	Ge(8.974)	Po(0.000)	Po(3.396)	Po(0.967)	Po(0.091)
17	Ge(41.58)	Ge(12.77)	Ge(23.12)	Po(0.012)	Po(12.50)	Po(0.360)	Ge(3.343)	Po(1.207)	Ge(20.33)	Po(0.055)	Po(9.041)	Po(0.067)	Po(0.321)
18	Nb(9.760)	Nb(6.335)	Nb(1.630)	Ge(23.06)	Ge(7.194)	Po(1.500)	Ge(6.152)	Po(0.288)	Po(4.661)	Po(1.782)	Po(10.69)	Po(0.767)	Po(1.589)
19	Ge(9.953)	Nb(13.95)	Ge(2.336)	Ge(58.22)	Ge(7.710)	Po(0.957)	Nb(31.37)	Po(0.073)	Po(2.350)	Po(0.060)	Ge(1.085)	Po(1.656)	Po(4.694)
20	Ge(9.149)	Ge(7.233)	Po(6.880)	Ge(10.41)	Ge(0.030)	Po(0.735)	Ge(9.549)	Po(0.000)	Ge(1.987)	Po(0.000)	Po(5.122)	Po(0.003)	Po(3.176)
21	Ge(6.625)	Nb(8.999)	Po(15.96)	Po(2.686)	Po(5.818)	Po(3.267)	Ge(21.75)	Po(0.000)	Ge(10.87)	Po(0.375)	Ge(6.601)	Po(13.40)	Po(0.104)
22	Ge(6.992)	Ge(9.500)	Nb(1.987)	Ge(11.54)	Po(3.059)	Po(2.475)	Ge(2.209)	Po(0.000)	Ge(4.988)	Po(0.000)	Ge(6.006)	Po(6.356)	Po(2.769)
23	Nb(11.97)	Nb(2.013)	Ge(18.26)	Po(1.613)	Po(4.503)	Po(2.244)	Ge(1.199)	Po(2.662)	Ge(2.305)	Po(0.000)	Ge(6.006)	Ge(6.671)	Ge(14.74)
24	Ge(4.646)	Ge(3.521)	Un(3.000)	Po(7.420)	Ge(7.038)	Po(2.369)	Ge(8.786)	Po(1.646)	Nb(0.786)	-	Ge(0.585)	Po(7.476)	Po(13.53)
25	Ge(9.642)	Ge(4.260)	Nb(0.669)	Po(0.016)	Po(10.59)	Po(1.263)	Ge(4.022)	Po(0.000)	Po(17.87)	Po(0.000)	Ge(0.617)	Po(1.865)	Po(0.000)
26	Ge(3.765)	Ge(1.135)	Po(6.761)	Po(0.000)	Ge(4.493)	Po(0.276)	Ge(2.343)	Po(0.000)	Ge(3.509)	Po(0.000)	Ge(1.783)	Po(0.097)	Po(0.000)

Note: () indicates chi-square value. Note: Discrete distributions: Nb = Negative binomial; Po = Poisson Ge = Geometric; Bi = Binomial; Un = Uniform.

Table 8 shows the mean and standard deviation for the repair frequency distribution determined by the goodness-of-fit test for each cell. As shown in Table 8, a frequency distribution was generated in various patterns for most cells. This is because the actual repair times of various finishing works vary greatly because of diverse causes, such as materials, location characteristics of construction, and user carelessness, unlike the expected repair times. This suggests that the long-term maintenance plan needs to consider the uncertainty of damage caused by the various characteristics of the finishing works.

Table 8. Statistics of repair frequency distributions for each cell.

Repair Time (Year)	Finishing Work																								
	I				DW					P			T		FD			F		W				PL	CA
	1	2	3	4	1	2	3	4	5	1	2	3	1	2	1	2	3	1	2	1	2	3	4		
7	8.10 (2.00)	8.15 (2.06)	- (-)	0.05 (0.22)	- (-)	- (-)	0.15 (0.39)	- (-)	- (-)	0.80 (0.89)	- (-)	- (-)	0.50 (0.71)	0.10 (0.32)	- (-)	- (-)	- (-)	- (-)	0.30 (0.55)	0.05 (0.22)	0.10 (0.32)	- (-)	0.10 (0.32)	- (-)	- (-)
8	40.8 (40.3)	40.0 (39.5)	0.85 (0.92)	0.05 (0.22)	1.25 (0.68)	- (-)	0.85 (0.92)	0.15 (0.39)	0.30 (0.55)	2.85 (2.30)	0.45 (0.67)	- (-)	1.70 (1.09)	0.45 (0.67)	0.25 (0.50)	0.10 (0.32)	0.20 (0.45)	- (-)	4.35 (3.82)	0.25 (0.50)	1.40 (0.75)	- (-)	0.35 (0.59)	0.05 (0.22)	- (-)
9	14.9 (7.66)	12.3 (3.50)	0.25 (0.50)	- (-)	2.70 (2.14)	0.20 (0.45)	34.4 (33.9)	0.50 (0.71)	0.50 (0.71)	4.75 (4.22)	2.80 (2.24)	- (-)	2.60 (2.04)	0.95 (0.97)	0.75 (0.87)	0.45 (0.67)	0.70 (0.84)	0.40 (0.63)	7.60 (2.76)	0.25 (0.50)	0.75 (0.87)	0.05 (0.22)	0.75 (0.87)	0.05 (0.22)	0.20 (0.45)
10	25.7 (17.4)	22.6 (22.1)	0.44 (0.66)	- (-)	1.16 (1.08)	0.04 (0.20)	1.68 (1.07)	0.32 (0.57)	0.32 (0.57)	4.88 (4.35)	1.96 (1.37)	0.04 (0.20)	3.16 (2.61)	0.80 (0.89)	0.76 (0.87)	0.40 (0.63)	0.60 (0.77)	0.96 (0.98)	7.84 (7.32)	0.08 (0.28)	0.76 (7.87)	0.04 (0.20)	0.56 (0.75)	0.12 (0.35)	0.52 (0.72)
11	7.69 (7.17)	5.46 (4.93)	0.06 (0.24)	0.14 (0.38)	0.23 (0.48)	- (-)	0.51 (0.72)	0.03 (0.17)	0.17 (0.41)	3.03 (2.48)	1.71 (1.11)	- (-)	2.80 (2.24)	0.91 (0.96)	0.31 (0.56)	0.03 (0.17)	0.17 (0.41)	0.26 (0.51)	3.06 (2.51)	0.17 (0.41)	1.11 (1.06)	0.03 (0.17)	0.74 (0.86)	- (-)	0.69 (0.83)
12	11.8 (11.3)	6.00 (3.46)	0.49 (0.70)	- (-)	0.91 (0.96)	0.34 (0.59)	49.5 (49.0)	0.26 (0.51)	0.23 (0.48)	4.17 (3.64)	2.83 (2.27)	- (-)	3.40 (2.86)	0.80 (0.89)	0.80 (0.89)	0.17 (0.41)	1.11 (0.36)	0.26 (0.51)	4.71 (4.18)	0.26 (0.51)	0.54 (0.74)	- (-)	0.29 (0.53)	0.23 (0.48)	0.86 (0.93)
13	14.7 (14.2)	8.56 (8.05)	0.59 (0.77)	0.18 (0.42)	1.38 (0.65)	0.23 (0.48)	1.64 (1.03)	0.15 (0.39)	0.41 (0.64)	7.82 (7.30)	2.72 (2.16)	- (-)	5.38 (4.86)	1.51 (0.88)	1.49 (0.85)	0.31 (0.55)	1.15 (1.07)	0.36 (0.60)	3.18 (2.63)	0.15 (0.39)	1.28 (1.13)	0.08 (0.28)	0.46 (0.68)	0.21 (0.45)	0.64 (0.80)
14	12.2 (11.7)	10.6 (10.1)	0.67 (0.82)	0.13 (0.36)	0.77 (0.88)	0.08 (0.28)	1.72 (1.11)	0.08 (0.28)	0.26 (0.51)	3.97 (1.98)	2.26 (1.68)	0.13 (0.36)	6.64 (6.12)	1.13 (0.38)	1.18 (0.46)	0.03 (0.16)	1.03 (1.01)	0.05 (0.23)	2.51 (1.95)	0.05 (0.23)	1.77 (1.17)	- (-)	0.59 (0.77)	0.03 (0.16)	0.03 (0.16)
15	9.90 (9.38)	5.10 (2.81)	0.87 (0.93)	0.05 (0.23)	0.96 (0.93)	0.41 (0.64)	1.85 (1.25)	0.36 (0.60)	0.28 (0.53)	2.87 (2.32)	1.79 (1.19)	0.03 (0.16)	15.3 (14.8)	0.79 (0.89)	1.90 (1.30)	0.08 (0.28)	1.21 (1.10)	0.21 (0.45)	7.51 (6.99)	0.13 (0.36)	1.72 (1.11)	0.21 (0.45)	0.33 (0.58)	0.15 (0.39)	0.10 (0.32)
16	29.0 (28.5)	15.2 (14.7)	0.87 (0.93)	0.15 (0.38)	1.81 (1.22)	0.28 (0.53)	2.41 (1.84)	0.20 (0.45)	2.24 (1.67)	3.06 (2.51)	0.63 (0.79)	0.02 (0.14)	5.02 (4.49)	1.17 (0.44)	1.57 (0.95)	0.15 (0.38)	0.85 (0.92)	0.56 (0.75)	3.93 (3.39)	0.06 (0.24)	1.65 (1.03)	0.07 (0.27)	0.24 (0.49)	0.28 (0.53)	0.11 (0.33)
17	9.81 (9.30)	3.61 (3.07)	0.93 (0.96)	0.09 (0.30)	1.61 (0.99)	1.01 (0.10)	2.44 (1.88)	0.35 (0.59)	1.57 (0.95)	2.39 (1.82)	0.20 (0.45)	0.04 (0.19)	4.69 (4.16)	1.61 (0.99)	1.11 (0.35)	0.17 (0.41)	0.83 (0.91)	0.22 (0.47)	1.22 (0.52)	0.31 (0.56)	2.70 (2.15)	0.13 (0.36)	0.67 (0.82)	0.22 (0.47)	0.15 (0.38)
18	12.3 (7.98)	6.76 (6.24)	2.09 (1.51)	0.09 (0.30)	4.47 (3.94)	0.42 (0.65)	3.16 (2.61)	0.87 (0.93)	2.73 (2.18)	4.07 (3.53)	1.13 (0.39)	0.02 (0.15)	3.64 (3.10)	3.87 (3.33)	4.73 (4.20)	3.71 (3.17)	4.44 (3.91)	0.71 (0.84)	2.42 (1.86)	0.18 (0.42)	4.16 (2.04)	0.38 (0.61)	0.93 (0.97)	0.80 (0.89)	0.56 (0.75)
19	17.2 (11.4)	8.84 (8.33)	2.56 (1.99)	0.07 (0.26)	5.84 (3.35)	0.40 (0.63)	4.16 (3.62)	0.60 (0.77)	2.07 (1.48)	4.87 (4.34)	1.31 (0.64)	0.02 (0.15)	3.64 (3.10)	3.33 (2.79)	7.16 (6.64)	5.53 (5.01)	3.89 (3.35)	0.44 (0.67)	4.36 (2.26)	0.18 (0.42)	5.49 (2.34)	0.29 (0.54)	1.29 (0.61)	0.62 (0.79)	0.60 (0.77)
20	19.8 (19.3)	4.84 (4.32)	2.11 (1.53)	0.22 (0.47)	4.24 (3.71)	0.38 (0.61)	4.40 (3.87)	0.33 (0.58)	2.71 (2.51)	6.69 (6.17)	1.11 (0.35)	0.07 (0.26)	3.13 (2.59)	3.91 (3.37)	2.89 (1.70)	2.04 (1.46)	1.27 (0.58)	0.47 (0.68)	9.07 (8.55)	0.04 (0.21)	4.29 (3.76)	0.07 (0.26)	0.78 (0.88)	0.38 (0.61)	0.47 (0.68)
21	13.7 (13.2)	5.68 (5.15)	2.38 (1.81)	0.25 (0.50)	4.82 (4.30)	0.10 (0.32)	2.65 (2.09)	0.30 (0.55)	2.03 (1.44)	6.55 (6.03)	1.05 (0.23)	0.70 (0.84)	3.33 (2.78)	3.18 (2.63)	2.33 (1.52)	0.70 (0.84)	1.13 (1.06)	0.45 (0.67)	3.58 (3.03)	0.10 (0.32)	6.70 (6.18)	0.18 (0.42)	1.95 (1.36)	1.03 (1.01)	0.25 (0.50)
22	24.3 (11.1)	4.83 (4.30)	3.07 (2.52)	0.27 (0.52)	5.83 (3.34)	0.10 (0.32)	3.50 (2.96)	0.10 (0.32)	2.37 (1.80)	9.53 (5.99)	4.10 (3.57)	2.03 (1.45)	2.67 (2.11)	4.90 (4.37)	3.83 (3.30)	2.10 (1.52)	1.10 (1.05)	0.30 (0.55)	10.9 (10.4)	0.07 (0.26)	7.70 (7.18)	0.13 (0.37)	5.77 (5.24)	2.00 (1.41)	0.60 (0.77)
23	36.8 (17.4)	8.47 (7.95)	3.83 (3.30)	0.27 (0.52)	7.83 (7.32)	0.17 (0.41)	4.27 (3.73)	0.07 (0.26)	2.77 (2.21)	15.9 (10.5)	1.00 (1.00)	3.13 (2.59)	3.17 (2.62)	3.63 (3.09)	6.23 (5.71)	0.37 (0.61)	0.43 (0.66)	0.70 (0.84)	12.8 (12.3)	0.53 (0.73)	8.90 (8.39)	0.17 (0.41)	5.77 (5.24)	2.30 (1.73)	2.23 (1.66)
24	27.5 (15.0)	5.65 (5.13)	2.50 (1.94)	0.31 (0.55)	5.31 (4.78)	0.19 (0.44)	2.50 (1.94)	0.27 (0.52)	3.46 (2.92)	6.46 (5.94)	1.69 (1.08)	0.65 (0.81)	3.65 (3.11)	3.27 (2.72)	6.00 (3.74)	0.96 (0.98)	2.23 (1.66)	1.31 (1.14)	15.2 (14.7)	0.31 (0.55)	3.23 (2.68)	- (-)	1.96 (1.37)	0.77 (0.88)	1.00 (1.00)
25	13.4 (8.70)	4.04 (3.50)	1.69 (1.30)	0.23 (0.48)	2.46 (0.66)	0.08 (0.28)	1.81 (1.34)	0.23 (0.48)	2.27 (1.70)	2.92 (2.37)	0.54 (0.73)	0.69 (0.83)	2.19 (1.62)	2.04 (1.45)	5.62 (5.09)	0.38 (0.62)	2.73 (1.65)	0.54 (0.73)	10.7 (10.1)	0.12 (0.34)	2.96 (1.72)	0.08 (0.28)	1.73 (1.12)	0.65 (0.81)	0.08 (0.28)
26	9.88 (9.37)	2.23 (1.66)	0.96 (0.98)	0.15 (0.39)	3.15 (2.61)	0.73 (0.85)	0.77 (0.88)	0.04 (0.20)	1.77 (1.17)	2.38 (0.68)	0.42 (0.65)	2.58 (2.02)	2.15 (1.58)	2.58 (2.02)	4.65 (2.16)	0.15 (0.39)	2.04 (1.45)	0.27 (0.52)	6.54 (6.02)	0.15 (0.39)	4.50 (3.97)	0.08 (0.28)	1.88 (1.29)	0.23 (0.48)	0.12 (0.34)

Note: () indicates standard deviation.

4.3. Estimating Repair Time Distributions for Each Finishing Type

When the Monte Carlo simulation is performed with the repair time distribution for each cell, derived above based on Equation (1), the repair time distribution of each finishing work category can be generated, as shown in Figure 3. The statistics of the repair time distributions for each category are summarized in Table 9.

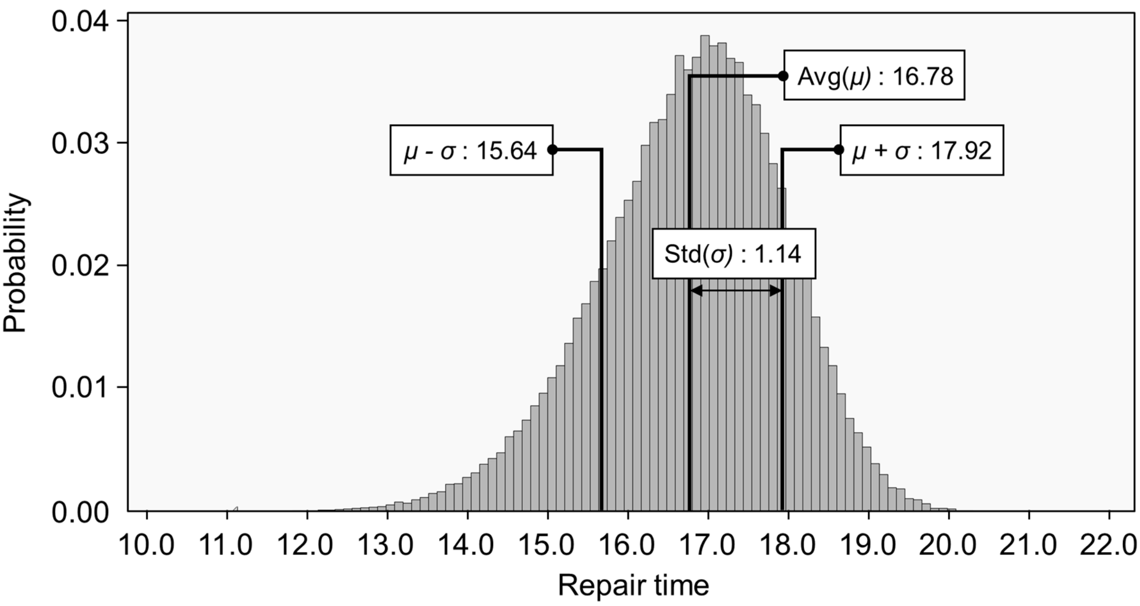

Figure 3. Repair time distribution example: Interior: wall.

Table 9. Statistics of repair time distributions.

Classification	Sub-Category	Statistics of Repair Time Distributions					
		Mean	Median	Mode	Standard Deviation	Skewness	Kurtosis
Interior (I)	Wall (I1)	16.78	16.86	17.00	1.14	−0.3748	3.17
	Floor (I2)	13.89	13.93	14.00	1.30	−0.0911	2.76
	Ceiling (I3)	19.85	19.88	20.00	0.91	−0.2197	3.01
	Molding (I4)	18.30	19.67	0.00	5.88	−1.9200	6.62
Door and windows (DW)	Wood (DW1)	19.59	19.62	20.00	0.82	−0.2577	3.18
	Steel (DW2)	18.28	18.29	17.00	2.06	−0.0709	2.79
	Plastic (DW3)	13.89	13.70	14.00	1.52	0.5518	3.11
	Aluminum (DW4)	16.61	16.75	18.00	2.66	−1.3800	10.65
	Window screen (DW5)	20.27	20.29	20.00	0.82	−0.1015	2.89
Painting (P)	Water paint (P1)	17.93	17.97	18.00	1.01	−0.1835	2.91
	Oil paint (P2)	16.04	16.00	16.00	1.07	0.1382	2.87
	Anti-sweating paint (P3)	23.35	23.40	23.00	0.76	−0.5356	4.04
Tiling (T)	Wall (T1)	16.47	16.42	16.00	0.76	0.3168	3.09
	Floor (T2)	19.48	19.50	19.00	0.80	−0.1337	3.03
Front door (FD)	Body (FD1)	20.47	20.48	20.00	0.76	−0.1286	3.03
	Doorframe (FD2)	19.14	19.15	19.00	0.88	−0.1901	3.56
	Components (FD3)	19.05	19.04	19.00	0.89	0.0855	3.12
Furniture (F)	General (F1)	18.31	18.36	18.00	2.04	−0.3427	4.93
	Kitchen (F2)	18.47	18.52	18.00	1.26	−0.2442	2.89
Waterproofing (W)	Membrane waterproofing (W1)	16.57	17.00	17.00	4.69	−1.2500	5.98
	Liquid waterproofing cement (W2)	19.88	19.90	20.00	0.76	−0.1987	3.05
	Sheet waterproofing (W3)	16.04	18.00	0.00	6.98	−1.5000	4.08
	Caulking (W4)	20.49	20.57	21.00	1.01	−0.4000	3.09
Plastering (PL)	-	20.91	21.00	21.00	1.15	−0.4571	3.48
Carpentry (CA)	-	18.39	18.38	18.00	1.79	0.0089	2.89

Table 9 shows the mean value of the repair time distribution for each finishing work, which can be considered as the deterministic repair time set in conventional maintenance planning. However, what is more important is to verify the statistics related to the pattern of repair time distribution in order to establish reasonable maintenance planning, taking into account the uncertainty of repair activity due to various causes. In this paper, the repair time distribution was examined using standard deviation, a representative uncertainty indicator for risk management. First, the repair time distributions of P3, T1, T2, FD1, and W2 were found to have smaller standard deviations than the other categories. This means that various values of the distribution have relatively small deviations around the mean value. As a result, it is necessary to plan intensive maintenance activities for a certain period around the mean value. In contrast, the repair time distributions of I4, DW2, DW4, W1, and W3 yielded high standard deviations. This implies that constant repairs for a relatively long time are required for these categories. A detailed review of each category indicated the need for a customized maintenance plan. In other words, the repairs for interior: molding (I4) could be caused by residents' carelessness. In contrast, waterproofing: membrane waterproofing (W1), and waterproofing: sheet waterproofing (W3) have a higher possibility of construction error than residents' carelessness because these waterproofing methods are mainly used in common spaces, such as underground parking lots or rooftops rather than indoor spaces. Furthermore, doors and windows: steel (DW2), and doors and windows: aluminum (DW4) were associated with cases that required repairs due to problems in material properties. Thus, customized maintenance risk management will be possible if the repair time distribution is confirmed based on detailed subcategories, instead of setting the repair time based on the finishing work types.

In order to develop an effective maintenance strategy that reflects uncertainty, we need criteria for setting the expected repair activity level for each point in time. Table 10 has a significant implication from this perspective. Table 10 summarizes the percentiles of repair time distribution according to the repair time. Through Table 10, an efficient maintenance plan can be established by checking the time when repairs are concentrated for each finishing work.

Table 10. Placements of percentiles based on category.

Repair Time (Year)	Finishing Work																								
	I				DW					P			T		FD			F		W				PL	CA
	1	2	3	4	1	2	3	4	5	1	2	3	1	2	1	2	3	1	2	1	2	3	4		
0				6.8				0.5												3.2		13.9			
1																									
2																									
3																									
4																									
5																									
6																									
7				0.3																0.2					
8				0.4				0.1												1.0					
9				0.1				0.5												1.4		0.7			
10		0.1		0.1				0.5										0.1		1.4		0.6			
11		1.3		1.3			1.0	0.6										0.1		2.1		0.5			
12		6.6		0.5		0.1	7.4	1.6										0.2		3.3		0.3			
13	0.1	17.4		2.0		0.8	21.6	3.2			0.1							0.5		4.4		1.7			0.1
14	1.3	27.1		2.4		1.6	27.8	6.5			2.3							1.3		5.7		1.4			0.7
15	5.4	27.3		2.6		4.6	20.0	10.5		0.2	14.9		1.7					3.4	0.4	8.0		5.0			2.6
16	16.4	15.4		4.6		8.1	12.0	15.0		3.0	33.2		26.7			0.1		7.1	2.6	10.0		4.9			6.9
17	31.3	4.2	0.2	6.0	0.3	14.3	6.3	17.7		14.9	31.1		48.4	0.2		1.2	1.0	12.8	9.7	11.3		8.4	0.1	0.3	13.3
18	31.2	0.5	2.6	7.8	3.0	17.6	2.7	17.0	0.4	33.3	14.7		20.1	3.6	0.1	8.4	11.0	18.3	21.7	11.4	1.0	14.3	1.2	1.2	19.8
19	11.9	0.1	15.1	9.7	19.7	18.4	0.7	12.8	6.4	33.9	3.5		2.9	23.8	3.0	34.3	37.6	20.5	30.2	9.8	11.6	14.6	7.0	5.0	21.7
20	1.4		38.0	11.5	45.7	15.1	0.1	7.4	31.4	13.0	0.3	0.1	0.1	46.7	24.1	41.4	36.7	17.1	24.1	7.9	42.5	10.1	21.9	15.5	17.6
21			34.7	11.9	28.0	10.8		3.7	43.6	1.3		0.6		23.2	48.7	13.0	12.1	10.8	9.4	6.1	38.5	9.5	37.9	30.5	10.8
22			9.0	10.6	3.3	6.0		1.5	16.9			4.9		2.4	22.4	1.4	1.5	5.1	1.3	4.1	6.1	6.2	27.2	32.2	4.7
23			0.4	9.4	0.0	2.3		0.5	1.3			25.6			1.7		0.1	2.0		4.2	0.1	4.3	4.6	13.6	1.7
24				7.0		0.4		0.3				52.2						0.6		2.9		0.9	0.1	1.6	0.4
25				3.6				0.2				16.1						0.1		1.1		1.4		0.1	
26				1.4								0.6								0.6		1.2			

Furthermore, the percentile described in each cell of Table 10 can be regarded as the likelihood that certain repair work should be done at a given time. One of the conventional maintenance plans is to set a uniform maintenance budget on a monthly or yearly basis. As a result, we may miss the optimal repair time due to an insufficient budget to cover the actual maintenance costs. This phenomenon is caused by insufficient consideration of the level of performance degradation of the building. In other words, the conventional maintenance plan must assume that the performance of various components of a building degrades at the same rate each year. However, based on the results of this study, it is clear that this assumption is not rational. When we use the results in Table 10 as weights, the resources required for repair can be allocated efficiently by reflecting the uncertainty of repair. This demonstrates the possibility of overcoming the limitations of a conventional maintenance plan and establishing a performance-oriented building maintenance system.

5. Discussion and Conclusions

The aim of this study was to outline the implications pertaining to the establishment of efficient maintenance strategies for residential buildings by analyzing the uncertainty of the repair times of various finishing works according to probabilistic methodologies.

To this end, this study collected 47,344 repair data for 63 buildings in 12 public residential building complexes completed between 1991 and 2001 in South Korea. The uncertainty of repair times for finishing works was reflected by deriving the repair frequency distribution using a probabilistic approach that surpassed the limitations of deterministic methods.

As a result of analyzing repair time distributions, there were specific repair times when intensive maintenance activities were required for finishing works with relatively small uncertainties, such as anti-sweating paint, wall and floor tiles, front doors, and liquid waterproofing cement. In addition, continuous maintenance activities are required for molding, doors and windows made of steel or aluminum, membrane waterproofing, and sheet waterproofing, because the times at which repairs were required were distributed.

Furthermore, as a result of the repair time distribution percentiles in the repair time matrix, it is considered that the maintenance plan set with the existing uniform criteria can be improved. If there are no criteria for assessing the performance level of the building or the need for repair, the annual maintenance budget will be a fixed percentage of the rent. However, the annual cost for repairing building components damaged by various causes is irregular. As a result, if the maintenance budget is lower than the actual maintenance cost, the appropriate maintenance time may be missed. Furthermore, if the maintenance budget is larger than the actual maintenance cost, the remaining funds may be used inefficiently.

The percentile of the repair time distribution derived from this study can be regarded as the likelihood that each finishing work requires repair at some point. The possibility of a repair occurring at any given point in time can be used as a weight when developing an efficient maintenance plan. This means that the efficient distribution of limited resources is viable. The findings of this study are expected to be applicable to the development of a performance-oriented maintenance system for public residential buildings.

Moreover, even if passive and active technologies are applied to various components of residential buildings for energy savings, it is essential to efficiently maintain the performance of these technologies to ensure the sustainability of residential buildings. In this sense, the results of this study can contribute to securing the sustainability of residential buildings.

In the Republic of Korea, the repair times that are officially presented in maintenance plans are the result of a deterministic approach. However, the probabilistic approach applied in this study can provide various information for reasonable maintenance decision making for each finishing work in addition to the basic repair time setting. In other words, a probabilistic approach can be adopted as a critical decision-making method because the performance of various finishing works is practically degraded owing to complex causes, causing uncertainty in the repair time of each category. Furthermore, the scope of finishing works addressed in maintenance plans is limited. This implies that more unexpected repairs can occur. In this context, the result of the repair time distribution based on the subcategory derived in this study is expected to contribute to the effective establishment of maintenance plans by maintenance managers.

The amount of data is the fundamental limitation of a data-driven model. Since the repair data did not exist for specific cells in this study, analysis was performed by setting them to zero. If enough repair data can be allocated to the repair time matrix established in this study, it is expected that improved analysis results will contribute to the development of a more systematic maintenance strategy. Furthermore, in order to ultimately improve maintenance efficiency, building damage should be avoidable in advance. To do so, we have to identify the causes of damage, and more research is needed to identify key factors that influence the degradation of building performance. Finally, a detailed analysis of repair cost, as well as frequency, is required to establish an effective maintenance plan. However, the repair cost is not clear. In other words, the actual repair cost statements often combine the costs of several finishing works instead of calculating them individually for specific finishing works. Thus, the quality of cost data needs to be improved to accurately calculate the effective maintenance cost. Although this study focused on repair time owing to the limitation of data collection, it is believed that flexible maintenance strategies can be established if probabilistic methods can be developed by simultaneously considering frequency and data with additional high-quality cost data.

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