Cost assessment model for sustainable health and safety management of high-rise residential buildings in Korea

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Abstract

The accident rate in the Korean construction industry is much higher compared to the one in other industries. One of the main reasons for this problem is the health and safety management cost (HSC) estimation method which does not reflect the project features at construction sites. In Korea, health and safety management cost is estimated by applying a legally designated ratio in proportion to construction cost without reflecting construction features, such as the building’s shape, number of floors, and construction period. However, such a method does not fulfill the cost for the gradually strengthening safety management of high-rise residential buildings. Therefore, the objective of this paper is to develop a cost assessment model for sustainable health and safety management of high-rise residential buildings. For this purpose, actual data of 23 completed projects were collected and analyzed to identify problems and influence factors of HSC assessment and to establish a regression model. By applying the model established for five new sites as a case, its validation was verified. The results of this study will be utilized as reference data for the HSC estimation method and its relevant policy establishment.

1. Introduction

The accident rate in the Korean construction industry is much higher compared to the one in other industries (Gurcanli, Bilir, and Sevim 2015; Walker and Tait 2004). According to the annual statistic of industrial accidents by the Occupational Safety and Health Agency in the Republic of Korea, while the overall industrial mortality rate per thousand decreased by ~1.22% from 7.05% in 2009 to 5.83% in 2019, it appeared to increase by ~3.61% from 6.55% in 2009 to 10.16% in 2019 in construction industry (Korea Occupational Safety and Health Agency 2019). One of the main reasons for this problem is the health and safety management cost (hereinafter to be referred to as HSC) estimation method which does not reflect the project features at construction sites (Hamid, Singh, and Mohd 2020; López-Alonso et al. 2013; Yoon et al. 2013).

Direct factors affecting critical accidents in building construction are the construction difficulty, which is the physical characteristic of the building, the urgency of the construction period including acceleration work, and the inadequate responses to unexpected situations on site. If HSCs corresponding to the direct...
factors are not allocated, it is clear that appropriate H&S tasks are not performed. Indirect factors are very diverse, including safety culture, safety atmosphere, safety leadership, safety-related management policies, and so on. It is difficult to create an H&S management solution by reflecting all of these factors. It is difficult to obtain relevant data, and it is more difficult to integrate them. However, when considering actual data collected from the site, it is possible to study the HSC estimated by the direct factors. In other words, for mitigation of high mortality rate and sustainable H&S management, HSC calculation studies corresponding to the direct factors listed above must precede the measures for indirect factors.

In Korea, for estimating the health and safety management cost, a legally defined designated ratio based on construction cost is applied without reflecting construction safety risks of buildings, such as the building’s shape and the number of floors (Son, Gal, and Yang 2007). According to the Occupational Safety and Health Act of Ministry of Employment and Labor in the Republic of Korea, Article 72 (Appropriation, etc. of Funds for Occupational Safety and Health Management), Clause 1, the differential ratio of HSC is applied in accordance with five construction types (Ministry of Employment and Labor 2019a). However, this method of estimation does not fulfill the cost based on the strengthened safety management and construction safety risk features such as the building’s shape and the number of floors are not reflected in safety facilities cost, which does not result in a sustainable safety management (Buica et al. 2017; Bianchini et al. 2017; Choi and Loh 2017).

The quantity of external finishing works is linked to the building’s shape and the number of floors, affecting the construction cost. However, many of the works including structural work applies the unit price linked to the total floor area. Therefore, it is difficult to expect a reasonable HSC calculation that reflects construction safety risk features. In addition, due to the lowest price bid system with fierce bidding competition, HSC is often calculated by a legally designated ratio without establishing a detailed H&S management plan. In most cases, a detailed H&S management plan is established after winning a construction project, and in this case, if an H&S management plan corresponding to the reinforced codes and regulations is executed, the HSC will exceed the awarded H&S budget. As such, the gap between reality and the legal system causes problems in which poor H&S management is performed or budget is exceeded. In particular, according to the analysis of actual and planned data collected for this study, HSC unbalance is more severe for high-rise residential buildings with 30 floors and above, which increases the possibility of construction accidents. Therefore, institutional measures should be taken to assign the HSC corresponding to the construction safety risk features of buildings. If not, the possibility of a safety accident increases due to the inappropriate HSC assessment. The objective of this study is to develop a cost assessment model for sustainable health and safety management of high-rise residential buildings in Korea. The result of this study will contribute to a sustainable safety management of construction sites in real practice, and it will be utilized as reference data of the HSC estimation method and its relevant policy establishment academically.

2. Methodology

This study will be proceeded as shown in Figure 1. First, describe problems and influence factors of HSC assessment through preliminary study. Second, collect actual data on HSC of high-rise residential building projects in Korea, including construction management data in detail in addition to calculating influence factors of each project. Third, perform a correlation analysis of HSC and influence factors based on the collected data. Fourth, establish a cost assessment model for a sustainable health and safety management. Finally, verify its validation through applying the established model to a new project.

![Figure 1. Methodology.](image-url)
3. Preliminary study

3.1. Problem statement of HSC

As previously mentioned, “Appropriation and Use Standard of Industrial Health and Safety Management Cost in Construction Industry” based on a notification of Ministry of Employment and Labor in the Republic of Korea estimates HSC by designated ratios that are legally defined according to five project types and costs (Ministry of Employment and Labor 2019a). The problem associated with this method is that although HSC shall be allocated by reflecting project features, such as the building’s shape, number of floors, and construction period, an equivalent ratio in proportion to construction cost is applied to the projects that are classified in the same category. For example, in the case of a residential building project, the installation cost for safety facilities differs in accordance with the shape of a building and the number of floors; in conditions where the same size of gross floor area and the more floors there will be, the longer construction period will be, which resulted in an increased labor cost for the safety manager. However, HSC estimated on the basis of construction cost in proportion to the size of gross floor area is calculated almost in the same method. In addition, even small-scale construction with a low budget requires H&S managers in number more than a certain level. Additionally, the company itself pays for an additional cost under the current system due to the shortage of HSC.

In general, even in the same residential building, higher-rise buildings have higher risk factors such as worker and object falls, so safety facility installation costs are relatively high, so safety management costs should be allocated higher (Lee 2020). In addition, an Insufficient budget for safety management may eventually lead to a contraction of activities to prevent safety accidents, resulting in a vicious circle of increasing the likelihood of accidents (Baek 2020). Furthermore, the current system of industrial safety and health management cost does not provide estimation criteria for HSC reflecting the project features, but it classifies details of usage per item as shown in Table 1 (Ministry of Employment and Labor 2019b). Countries that appropriate certain ratios of construction cost when estimating the HSC like Korea are Switzerland and Japan (Reinhardt 2004; Horie 2010).

In Switzerland, HSC is appropriated differently by appropriation ratio per construction type based on the total construction cost as it is in Korea (Reinhardt 2004). As a result, it is a problem that a factor such as construction difficulty is not considered. In Japan, temporary work cost includes HSC, and project features are not taken into consideration as much as in Korea and Switzerland (Horie 2010). Argilés-Bosch et al. (2014) and Oxenburgh and Marlow (2005) pointed out that HSC of many construction projects is included in each item on the bill of quantity per construction type, and it is not classified as a separate item. In this case, the effects of project features on HSC are unidentifiable.

According to the notice “Appropriation and Use Standard of Industrial Health and Safety Management Cost in Construction Industry” of the Ministry of Employment and Labor in the Republic of Korea, items which can be used as HSC as shown in Table 1, which are labor cost and various work payments for H&S managers (H&S managers salary), safety facilities cost (safety facilities), personal protective and safety equipment purchase cost (personal protective equipment), safety inspection cost of business sites (safety inspection), costs for health and safety training and events (worker training cost), costs spent on health care of workers (worker health care cost), technical advice fee for construction disaster prevention (technical advice fee), and overhead cost used in head office (head office overhead).

When most contractors bid with the construction amount including HSC calculated by the actual H&S management plan, it is difficult to win projects in the competitive lowest price bidding system, so they bid with the HSC calculated at a legally designated ratio. And after winning a construction project, 100% of the HSC is budgeted according to the mandatory regulations of the law. However, due to continuously increasing labor cost, HSC is not being used in a well-balanced way due to facilities cost which resulted from a gradually reinforced safety management standard at most construction sites today (Cheon 2015). In particular, it is an issue that most of the HSC are being spent on H&S managers salary and safety facilities of Table 1, which causes the decrease of other items including the expense for workers’ health care and training. Consequently, if HSC corresponding with the strengthened policy is not allocated, then it can be problematic in managing the health and safety of workers continuously. Therefore, to achieve a sustainable safety management, a reasonable allocation of HSC is needed after the consideration of project features. Moreover, a reasonable assessment model for

| Item | Description |
|------|-------------|
| 1.   | H&S managers salary and additional work payments |
| 2.   | Safety facilities purchase and installation costs |
| 3.   | Personal protective equipment purchase and repair and maintenance costs |
| 4.   | Costs of various safety inspections performed by utilizing specialized agencies |
| 5.   | Costs spent on health and safety training of workers |
| 6.   | Costs spent on health care of workers |
| 7.   | Technical advice fee paid to agencies specialized in disaster prevention |
| 8.   | Overhead cost used in head office |
sustainable health and safety management shall be developed.

### 3.2. Influence factors of HSC

With the examination of the study on influence factors in HSC estimation, it is noted that Jin (2011) claimed that if a construction period lasts in a long term, the burden of H&S managers’ salary increases, which results in a lack of costs. He stated that in this case, safety facilities installation cost for safety net and preventing accidents by falling will become insufficient. Choi, Oh, and Kim (2014) pointed out that since HSC has been spent on the operation of safety managers more than on personal protective equipment, it is less likely to protect workers effectively from accidents. In particular, because the regulation on the allocation of costs has been strengthened without increasing HSC, it is difficult to distribute the budget in a balanced way. Therefore, a balanced H&S management cannot be achieved. To perform H&S management in a balanced way, the factors affecting HSC should be identified clearly. To analyze factors affecting HSC estimation, in this study, the actual HSC of 23 construction cases was investigated, and Pareto analysis was performed as shown in Figure 2(a).

As shown in Figure 2(a), safety facilities averaged 49.5%, and H&S managers salary averaged 32.6%, which was confirmed by the collected data. Personal protective equipment was analyzed at 9.8%, and workers’ health care (2.1%) and training (3.9%) were combined to be 6.0%. Since the sum of H&S managers salary and safety facilities is 82.1%, analysis of these two items according to Pareto’s law enables statistical calculation of the remaining five items including workers’ health care and training in Table 1 and Figure 2(a).

Therefore, in this paper, variables that can substitute for H&S managers salary and safety facilities are identified as influence factors, and are then used to build an HSC assessment model in Chapter 4. If we analyze details of usage per item on facilities cost in 23 case sites, as shown in Figure 2(b), the largest average usage ratio per item is safety net (68%), followed by safety fence (24%), opening cover (4%), toe plate (1%), and safety facilities for elevator openings (1%). In particular, the item which accounts for the highest ratio among the details on the usage of facilities cost is the cost spent on safety net installation. Therefore, in this study the quantity of safety net is selected as the main variable to reflect the effect of the continuously increasing facilities cost in the model of this study.

To give a more specific explanation of usage items on the labor cost of Figure 2(a), it is configured with salaries of safety and health managers, and safety monitoring corps who are additionally managed at some construction sites. In the case of construction cases, H&S management manpower (HSM) is investigated as shown in Table 2. For reference, the appointment of at least one safety and health manager is legally required in a construction with the total construction cost of more than 12 billion won or the number of all-time workers of more than 300 people in Korea (Ahn 2016). In addition, more than two safety and health managers are to be allocated in the management of construction cost that exceeds more than 80 billion won or the number of full-time workers is more than 600 people. Afterward, whenever an extra 70 billion won is added to the total construction cost or extra 300 full-time workers are supplemented, it is mandatory to appoint one additional safety and health manager.

However, since the lawfully regulated number of safety managers has a limitation in an effective safety

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**Figure 2.** Pareto analysis of HSC (Exchange rate: 1,219.50 Won/USD as of 31 March 2020, Bank of Korea).

**Table 2.** HSM status of case projects (Unit: man-month).

| Proj | SM* | HM* | SMC* | Total | Project | SM | HM | SMC | Total |
|------|-----|-----|------|-------|---------|----|----|-----|-------|
| 1    | 264 | 39  | 127  | 430   | 13      | 164| 36 | 56  | 256   |
| 2    | 80  | 29  | -    | 109   | 14      | 141| 32 | 48  | 203   |
| 3    | 84  | -   | 17   | 101   | 15      | 129| 40 | 48  | 217   |
| 4    | 59  | -   | 59   | 118   | 28      | 182|    |     |       |
| 5    | 71  | 28  | -    | 99    | 17      | 156| 34 | -   | 190   |
| 6    | 69  | 29  | 24   | 122   | 18      | 49 | -  | 48  | 97    |
| 7    | 79  | 41  | 25   | 145   | 19      | 207| 49 | 231 | 487   |
| 8    | 115 | 33  | 79   | 227   | 20      | 52 | -  | 39  | 91    |
| 9    | 57  | 28  | 19   | 104   | 21      | 74 | 22 | 82  | 178   |
| 10   | 51  | 23  | 21   | 100   | 22      | 75 | 28 | 78  | 181   |
| 11   | 110 | 31  | 73   | 214   | 23      | 85 | -  | 82  | 167   |
| 12   | 72  | 30  | 29   | 131   |         |    |    |     |       |

*Safety managers, **Health managers, ***Safety monitoring corps.
management, in many construction sites, safety monitoring corps that support the safety management work are in operation (Park 2018). At this point, since the safety monitoring corps are not lawfully regulated, all costs for their management shall be paid by the company. For a sustainable safety management, a sufficient number of workers including the safety monitoring corps will be allocated to comply with the strengthened regulation. Therefore, we define the health and safety managers, as well as the safety monitoring corps as the health and safety manpower (HSM) and select these as the influential factors of the proposed model.

Robson et al. (2007) stated that high-rise residential buildings today not only secure efficient spaces but also are specially designed to reflect various differentiated exterior designs to stimulate the consumer’s desire to buy them. These buildings with complicated exterior shapes have a relatively longer perimeter than square type buildings which leads to the increase of safety facilities installation costs for a safety net, safety fence, and toe plate for safety. For instance, as shown in Figure 3, when comparing three different types of buildings with the same building area and gross floor area, the building area of a square type building with the length of one side as B m has the building area of B² m², and the perimeter as 4B m. As shown in Figure 3(b), the rectangular type building with the length of one side as 2B m, B/2 m has the same building area. However, its perimeter is 5B m, which is 25% longer than the square type. The polygonal type building of Figure 3(c) also has the same building area, but its perimeter is 20B/3 m, which is about 67% longer than the square type. Hence, the more complicated the exterior shape of the building gets, the longer the perimeter becomes, which leads to the increase of safety facilities cost. Thus, the shape coefficient is a very significant influence factor reflecting the project features. For reference, the shape coefficient is also used to estimate the difference in external finish cost depending on the shape of a building (Kim, Kim, and Kim 1990; Bathurst and Butler 1973; Ferry, Brandon, and Ferry 1999; Kim 1991).

After analyzing the correlation between the difference between actual and planned HSCs and the shape types of the buildings for 23 projects collected for this study, a statistically high correlation was confirmed between them as shown in Figure 4. And it was confirmed as an R² value of 0.873 as shown in Table 3. As a result, it is logically confirmed that the more complex the building-shaped, the more the actual HSC increases than the planned HSC.

Furthermore, as the number of floors of a building increases, the number of layers for installing safety net increases, which leads to the increase in safety facilities cost (An et al. 2007). Most of the case projects in this study are high-rise buildings with more than 30 floors, and the number of floors of each building varies.

![Figure 3. Example of building shapes.](image)

![Figure 4. Scatter diagram analysis.](image)

| Table 3. Regression analysis between building shape and HSC difference. |
|---------------------------------------------------------------|
| Model | Unstandardized coefficients | Standardized coefficients |
|-------|------------------------------|---------------------------|
|       | B    | Std. error | Beta | t | Sig. | R² | R² adj. |
| Constant | 1.324 | 0.075 | | 17.705 | 0.000 | 0.873 | 0.867 |
| Difference | 0.003 | 0.000 | 0.934 | | 12.012 | 0.000 |
Particularly, HSC reflecting the number of floors will be estimated.

Hence, the safety facilities cost increases if the exterior shape of a building is complex or if a building is a high-rise. Therefore, HSC reflecting the building shape and number of floors will be estimated. Also, even for a similar project, HSC will be estimated differently depending on construction difficulty. Thus, in this study, the building’s shape factor and the number of safety net layers are used to define the construction difficulty as shown in Equation (1).

\[
CD = SF \times NS.
\]

Equation (1)

where \( CD \): construction difficulty; \( SF \): shape factor; \( NS \): number of safety net layers.

The construction difficulty of Equation (1) is estimated by multiplying the shape factor (SF) with the number of safety net layers (NS). As shown in Equation (2), the SF is estimated by dividing the building perimeter with the perimeter in the case of the square type, i.e. the SF of the case building is expressed as a relative ratio of the building when the SF of the square type building is defined as 1. For example, if the SF of Figure 3(a) is defined as 1, Figure 3(b) can be calculated as \( SF = \frac{20B}{\sqrt{2} \times 4} = 1.25 \) using Equation (2). Using the same method, Figure 3(c) calculates the SF as \( SF = \frac{20B}{\sqrt{2} \times 4} = 1.67 \).

\[
SF = L \div \left( \sqrt{A} \times 4 \right)
\]

Equation (2)

where \( L \): building perimeter; \( A \): building area.

Additionally, the projects in this study are configured with numerous buildings, and their exterior shapes and building areas are different from each other. In particular, their construction difficulties are different. Therefore, this study considers such different features of buildings to estimate the construction difficulty of each project as shown in Equation (3). The construction difficulty (CD) of Equation (3) is estimated by multiplying the shape factor of each building (SF) with the number of safety net layers for each building (NS), and the weighted average of construction difficulty of each building based on its building area. The process of estimating the CD using Equations (1), (2), and (3) are explained in detail with examples shown in Table 6 of Chapter 4.1.

\[
CD_i = \frac{1}{A_i} \sum_{j=1}^{n} (SF_j \times NS_j \times A_j)
\]

Equation (3)

where \( CD_i \): construction difficulty of each project; \( A_i \): total building area; \( SF_j \): shape coefficient of each building; \( NS_j \): number of floors per building with safety net installed; \( A_j \): building area of each building; \( i \): number of projects; \( j \): number of buildings. Hence, in this chapter, the factors affecting HSC estimation are analyzed. As a result, the quantity of safety net (QSN), HSM, and CD are selected as variables of the model.

4. Building an HSC assessment model

4.1. Data collection

We have collected the used amount of actual HSC and project features data on 43 construction sites since such data collection was implemented in 2016 in Korea. The investigation lasted for 9 months starting from March 2019. After closely reviewing the collected data, eight sites were excluded because of the unreliability of their data on HSM and volume on the safety net. Moreover, the analysis was performed on 23 sites.
Table 6. Actual HSC of case projects (Unit: 1,000 USD).

| Proj. | HSS^a | SF^b | PPE^c | SI^d | WTC^e | WHC^f | TAF^g | Total |
|-------|-------|------|-------|------|-------|-------|-------|-------|
| 1     | 1,506 | 2,453 | 349   | 60   | 103   | 88    | 8     | 4,567 |
| 2     | 247   | 328   | 152   | 21   | 30    | 16    | 6     | 794   |
| 3     | 410   | 344   | 91    | 31   | 35    | 16    | 92    | 974   |
| 4     | 207   | 440   | 116   | 22   | 29    | 20    | 834   |       |
| 5     | 486   | 1,076 | 170   | 29   | 43    | 44    | 1,847 |       |
| 6     | 394   | 577   | 125   | 16   | 33    | 30    | 2,177 |       |
| 7     | 492   | 635   | 110   | 34   | 10    | 13    | 1,294 |       |
| 8     | 739   | 1,255 | 256   | 38   | 80    | 78    | 2,445 |       |
| 9     | 280   | 578   | 130   | 16   | 40    | 25    | 1,070 |       |
| 10    | 303   | 669   | 114   | 19   | 13    | 16    | 1,138 |       |
| 11    | 827   | 1,018 | 351   | 23   | 62    | 33    | 2,312 |       |
| 12    | 561   | 1,008 | 144   | 20   | 59    | 34    | 1,826 |       |
| 13    | 975   | 1,569 | 317   | 42   | 93    | 70    | 3,065 |       |
| 14    | 767   | 1,486 | 303   | 32   | 35    | 67    | 2,690 |       |
| 15    | 672   | 1,109 | 199   | 34   | 39    | 52    | 2,106 |       |
| 16    | 629   | 1,559 | 289   | 40   | 43    | 32    | 2,986 |       |
| 17    | 558   | 1,365 | 258   | 63   | 56    | 43    | 2,344 |       |
| 18    | 280   | 665   | 89    | 19   | 51    | 36    | 1,140 |       |
| 19    | 1,419 | 2,244 | 3,501 | 115  | 119   | 84    | 7,483 |       |
| 20    | 292   | 676   | 134   | 10   | 59    | 13    | 1,184 |       |
| 21    | 668   | 1,032 | 394   | 32   | 69    | 23    | 2,221 |       |
| 22    | 539   | 813   | 86    | 47   | 74    | 28    | 1,587 |       |
| 23    | 643   | 1,539 | 135   | 84   | 54    | 41    | 2,497 |       |

^aH&S manager salary, ^bSafety facilities, ^cPersonal protective equipment, ^dSafety inspection, ^eWorker training cost, ^fWorker health care cost, ^gTechnical advice fee. Exchange rate is 1,219.50 Won/USD as of 31 March 2020 (Bank of Korea).

Table 7. Influence factor values of the case projects.

| Proj. | HSM | QSN^a | CD | Proj. | HSM | QSN | CD |
|-------|-----|-------|----|-------|-----|-----|----|
| 1     | 430 | 253,275 | 21.55 | 13 | 256 | 105,155 | 21.42 |
| 2     | 109 | 73,610  | 4.85  | 14 | 203 | 94,243  | 19.00 |
| 3     | 101 | 63,111  | 13.12 | 15 | 217 | 109,398 | 17.06 |
| 4     | 59  | 36,097  | 7.82  | 16 | 182 | 197,987 | 13.85 |
| 5     | 99  | 99,758  | 13.89 | 17 | 190 | 150,397 | 12.54 |
| 6     | 122 | 59,679  | 13.04 | 18 | 97  | 61,891  | 9.21 |
| 7     | 145 | 45,706  | 5.29  | 19 | 487 | 230,275 | 20.14 |
| 8     | 227 | 110,773 | 17.45 | 20 | 91  | 69,891  | 12.08 |
| 9     | 104 | 63,613  | 7.75  | 21 | 178 | 216,510 | 10.33 |
| 10    | 100 | 64,891  | 13.99 | 22 | 181 | 75,891  | 10.17 |
| 11    | 214 | 226,510 | 16.81 | 23 | 167 | 187,987 | 8.35 |
| 12    | 131 | 102,628 | 13.09 |       |       |       |     |

^aSafety net quantity (m²).

Table 8. Result of correlation analysis.

| Description | HSM | QSN | CD |
|-------------|-----|-----|----|
| HSC         | 0.924 | 0.827 | 0.749 |
| SP^a        | 0.000 | 0.000 | 0.000 |
| N           | 23   | 23  | 23  |

^aPearson Correlation Coefficient, ^bSignificance Probability.

As previously explained in Chapter 3.2, the major factors affecting HSC are HSM, the quantity of safety net, and CD. To explain the process of estimating the CD as an example, project 10 is configured with eight buildings, as shown in Table 6.

Among these, Building 1 has a building area of 619.70 m² and a perimeter of 182.00 m. Substituting these values in Equation (2) results in the SF of Building 1 as 1.83, as shown in Equation (4). Particularly, this means that Building 1 has a relatively complicated external shape compared to square-type buildings with the same building area. Furthermore, the safety net will be installed at a length 83% longer than in the case of square type. In this way, since the shape factors even in the same building area are different among buildings, the length of a safety net as well as its relevant facilities cost area differs.

\[
SF_1 = L_1 \div \left( \sqrt{A_1} \times 4 \right) = 182.00 \div \left( \sqrt{619.70} \times 4 \right) = 1.83
\]

(4)

In addition, Building 1 has 24 floors in total, and the safety net was installed on each of the seven layers based on the law mandating the installation within the gap of 10 m in height. Substituting this value in Equation (1) results in the CD of Building 1 estimated as 12.79. The CD of each building is estimated in the same method.

\[
CD_1 = SF_1 \times NF_1 \times A_1 \times \frac{74}{5.356} = 13.99
\]

(5)

Also, the CD representing a single project is calculated by the weighted average of CD of each building, as

\[
CD = \frac{1}{8} \sum_{j=1}^{8} (SF_j \times NF_j \times A_j) = 74,949.38
\]

(6)

which excluded 12 sites where final HSC details cannot be confirmed due to ongoing construction during the time of the investigation. Table 4 is the summary of projects selected as targets for final analysis.

As shown in Table 4, 23 selected projects have long-term construction proceeding with the average construction duration of 32 months and most of them are linked to high-rise buildings with more than 30 floors. Additionally, the case projects are configured with the average number of nine buildings and number of floors, and the building shapes of each building almost vary. Despite such features, HSC is being applied in the same ratio under the law. Table 5 shows the results of the investigation on the actual HSC of case projects. Since the implemented time of investigation on HSC is different across the case projects, they will be adjusted by base year to analyze the monetary value based on time difference equally. The investigated HSC was converted on the basis of the 2015 standard using the construction cost index announced by the Ministry of Land, Infrastructure, and Transport (Korea Institute of Civil Engineering and Building Technology 2020) as the deflator.
shown in Equation (6). The building area of each building is applied to weight. For project 10, the CD of the project is estimated to be 13.99 using Equation (3), as shown in Equation (6). The construction difficulties of 23 projects were estimated using the same method and HSM, as well as the quantity of safety net of each case project was investigated as shown in Table 7.

As shown in Table 7, data obtained from 23 sites were utilized to perform a correlation analysis of HSC, HSM, the quantity of safety net, and CD, and a cost assessment model was developed accordingly.

### 4.2. Data analysis

The correlation analysis between HSC and major factors using the collected data indicates relatively higher correlation coefficients of HSC, HSM, the quantity of safety net, and CD as 0.924, 0.827, and 0.749, respectively, as shown in Table 8. The p-value is <0.05 which is statistically meaningful. The factor which is most closely related to HSC is HSM, followed by the quantity of safety net, and CD. In particular, the high correlation between HSC and CD means that the building’s SF and the number of floors have a great impact on HSC.

Additionally, as a result of a regression analysis, a strong correlation is formed between HSC and HSM, and the regression model of Table 9 has a high suitability with R² value of 0.853. This indicates that HSC increases in proportion to the HSM, as shown in Figure 5(a). However, the existing method of estimating HSC with the lawfully designated ratio in proportion to construction cost does not reflect such features. As seen from the case projects, in numerous sites, an additional safety monitoring corps is in operation to fulfill the strengthened safety management standard, and all management costs are paid by the companies. Hence, to reflect the continuously increasing labor cost, HSC corresponding with the safety, health managers, and safety monitoring corps costs at construction sites shall be estimated. For reference, HSM is estimated at the construction planning phase and tied to the construction time.

As shown in Figure 5(b), a strong positive correlation is formed between HSC and the quantity of the safety net. According to Table 9, R² value of 0.684 has a relatively high suitability. This shows that the quantity of safety net affects the increase in HSC. However, the effect of the increasing facilities cost due to the strengthened regulation is not currently taken into consideration with the existing HSC estimation method. For the case projects, a large amount of cost for safety facilities is being paid in most of the sites. However, it was revealed that costs for safety training and health care of workers are relatively insufficient. Thus, HSC which reflects the quantity of safety net will be estimated to achieve a balanced H&S management, i.e. an HSC

**Figure 5.** Scatter diagram of HSC and influence factors.

### Table 9. Results of regression analysis.

| Model | Unstandardized coefficients | Standardized coefficients |
|-------|-----------------------------|---------------------------|
|       | B   | Std. error | Beta | t     | Sig. | R²  | R² adj |
| 1     | Constant | 4.476 | 2.096 | 2.135 | 0.045 | 0.853 |         |
|       | HSM  | 1.133 | 1.025 | 0.924 | 0.000 |         |         |
| 2     | Constant | 6.452 | 3.097 | 2.083 | 0.050 | 0.684 |         |
|       | QSN  | 15.560 | 2.311 | 6.734 | 0.000 |         |         |
| 3     | Constant | −14.668 | 4.920 | −0.298 | 0.603 | 0.603 |         |
|       | CD   | 20.105 | 3.558 | 5.651 | 0.000 |         |         |

**Table 10. Result of multiple regression analysis.**

| Model | Unstandardized coefficients | Standardized coefficients | Multicollinearity |
|-------|-----------------------------|---------------------------|-------------------|
|       | B   | Std. error | Beta | t     | Sig. | R²  | R² adj | Tolerance | VIF  |
| 1     | Constant | −1.926 | 2.276 | −0.846 | 0.408 | 0.930 | 0.919 | 0.291 | 3.432 |
| 2     | HSM  | 6.093 | 1.380 | 0.497 | 4.414 | 0.000 |         | 0.459 | 2.180 |
|       | QSN  | 5.360 | 1.688 | 0.338 | 3.768 | 0.001 |         | 0.473 | 2.116 |
| 3     | CD   | 6.387 | 2.287 | 0.247 | 2.793 | 0.012 |         |         |       |

...
estimation model based on the building’s shape is required.

As shown in Figure 5(c), a positive correlation is formed between HSC and CD, and R² value of 0.603 has a relatively fine suitability. Particularly, it indicates that the higher CD leads to the increase in HSC. CD is calculated by buildings’ shape factors and the number of floors constituting the projects as introduced in Equations (1)–(3). 5–20 in Figure 5(c) is the distribution of CD calculated by the collected data. If the building’s perimeter length and height are greater than the collected data, the CD value can be over 20. As seen from the case projects, the buildings’ shape factors and the number of floors vary in most cases although they are the similar kinds of residential buildings. Nevertheless, the method of estimating HSC under the current system is applied by the same ratio by law. This existing method does not reflect the CD at all, which has an urgent need for improvement of the estimation method.

4.3. HSC assessment model

In this chapter, a multiple regression analysis is performed, as shown in Table 10, based on factors analyzed in Chapter 4.2 to develop a cost evaluation model for safety management. As shown in Table 10, by adding three independent variables, the determinant factor (R²) of 0.930 has a quite high suitability for estimating HSC, and the adjusted determinant factor (adjusted R²), which reflected the degree of freedom, appeared to be 0.919. Additionally, the impact relation analysis between HSC and three major factors showed the following results: t-value of 4.415, p-value of 0.000 for HSM, t-value of 3.768, p-value of 0.001 for the quantity of safety net, and t-value of 2.793 and p-value of 0.012 for CD, which appeared to be relevant to HSC. In addition, as shown in Table 10, the correlations between the input variables such as HSM, QSN, and CD are reviewed, and the variance inflation factor (VIF) of HSM, QSN, and CD were calculated as 3.432, 2.180, and 2.116, respectively. The VIF of all input variables was less than 10, indicating that there was no problem with the multicollinearity between factors.

In general, the higher the CD, the more HSM and QSN are required. However, the existing calculation method in which the same ratio is uniformly applied to the same project type does not reflect the CD. This means that the HSM and QSN corresponding to the CD are not sufficiently reflected. This proves that there is no problem with the multicollinearity of the input variables. Therefore, we propose an HSC assessment model that reflects HSM, QSN, and CD.

Furthermore, when each is compared to one another in the category of the standardized coefficients, the largest coefficients are found to be HSM (0.497), followed by the quantity of safety net (0.338), and CD (0.247). Particularly, HSM is the factor influencing HSC the most among the three independent variables, and CD has a relatively less influence on HSC. The multiple regression analysis indicating this result can be expressed as shown in Equation (7).

\[ Y = 6.093 \times X_1 + 5.360 \times X_2 + 6.387 \times X_3 - 1.926 \]

where Y: health and safety cost (HSC); X₁: HSM; X₂: QSN; X₃: CD.

Using Equation (7), HSC can be estimated based on H&S management manpower (HSM), safety net quantity (QSN), and construction difficulty (CD). Unlike the current estimation method, the proposed regression model could reflect project characteristics, such as building shape, number of floors, and construction period. QSN and CD are associated with the building shape and number of floors as shown in Equations (1) to (3). And HSM is related to the construction period and reflects additional labor costs such as safety monitoring corps.

5. Validation of the model

Table 11 shows the summary of five new projects that were freshly investigated to verify the utility of the assessment model for HSC. The investigation lasted for 3 months starting from March 2020. The five new projects are for high-rise residential buildings, which consist of six buildings on average, have 33 floors on average, and last 32 months as the average construction period.

Table 12 is the results of the investigation on the actually used HSC in the five new case projects. The investigated HSC was converted based on the 2015 standard using the construction cost index as

| Proj. | Construction time | Duration (months) | Total floor area (m²) | Building area (m²) | No. of floors | No. of buildings | Total const. cost (1,000 USD) |
|-------|-------------------|-------------------|-----------------------|-------------------|---------------|-----------------|--------------------------|
| 1     | Dec. 2017 – Feb. 2020  | 27               | 77,970                | 3,628             | 29            | 6               | 76,394                   |
| 2     | Jul. 2017 – Nov. 2019 | 29               | 118,327               | 4,340             | 35            | 5               | 103,539                  |
| 3     | Jul. 2017 – Dec. 2019 | 30               | 112,816               | 5,758             | 25            | 8               | 109,255                  |
| 4     | Oct. 2016 – Jan. 2020 | 41               | 106,835               | 5,569             | 28            | 7               | 116,467                  |
| 5     | Oct. 2016 – May. 2019 | 31               | 183,737               | 10,856            | 49            | 6               | 188,266                  |
| Average |                   | 32               | 119,937               | 6,030             | 33            | 6               | 118,784                  |

Exchange rate: 1,219.50 Won/USD as of 31 March 2020 (Bank of Korea).
a deflator, as explained in Table 5, to analyze the monetary value equally at the time of execution.

Additionally, the HSM, safety net quantity, and CD of the five new projects were investigated, as shown in Table 13. At this point, the CD was estimated in the same method as explained in Table 6 and Equations (4) to (6).

Table 14 shows the comparison between the predicted HSCs (A) by applying Equation (7) to 5 new projects, the actually executed HSCs (B), and the existing HSCs (C) calculated according to the legally designated ratio. The predicted and actual HSCs show ratio differences of −3% to 8%, and the predicted and existing HSCs show differences of 6% to 18%. It is confirmed in Table 14 that the differences between the predicted and the actual HSCs are smaller than the differences between the predicted and existing HSCs. This means that the calculation method reflecting the construction characteristics such as construction difficulty, safety net quantity, and H&S manpower is more suitable for the calculation of actual HSC compared to the existing method where the legally designated ratio is applied to the construction cost.

In Table 14, when the predicted HSCs are more than the actual HSCs, the error range is 2–8%. The reason is that the construction time of the projects is relatively long, and the external shapes of the buildings are relatively complicated. And, when the predicted value is smaller than the actual value, it is one case and the error is −3%. This means that a surplus of 3% occurred in predicted HSC. It is confirmed that the project has a relatively short construction time and the external shapes of the buildings are relatively simple.

Figure 6 shows a graphical comparison of predicted, actual, and existing HSCs. As shown in Figure 6, the actual HSCs almost converge on the predicted HSC line, but the existing HSCs appear smaller than the predicted and actual HSCs in all five case projects. As a result of the analysis in Table 14 and Figure 6, it is confirmed that there is a problem with the existing HSC calculation method.

Through the major variable selection and model verification, we confirmed that the current HSC estimation method is not rational. Additionally, we also confirmed that if our proposed model is used, it is possible to achieve a cost assessment for a sustainable safety management. The result of this study can be utilized as reference data to improve the HSC policy in the future, and we expect that it will be developed into a more reliable model through a continuous data accumulation and verification of effectiveness.

6. Conclusion

To present a solution for improvement regarding the problems of the current HSC estimation, in this study, the actual data was used to establish a regression model, and its validation was verified through a case application. By using the proposed model, which enables HSC to be estimated from reflecting project features, such as input safety manpower, the quantity of safety net, and construction difficulty, a sustainable H&S management becomes possible. For this study, project data, such as actual HSC and construction characteristics of 23 construction sites, were collected and analyzed. Additionally, the model of five new projects was verified. The results of this study are as follows:

First, as a result of the performance of Pareto analysis on the collected data, it was confirmed that major factors affecting HSC were allocated safety manpower, quantity of safety net, and construction difficulty. As a result of conducting a correlation analysis between these three major factors and HSC, it was revealed that a strong positive correlation was made between them.
with Pearson correlation coefficients of allocated safety manpower as 0.924, the quantity of safety net as 0.827, and construction difficulty as 0.749. Furthermore, the result of the regression analysis indicated that the determinant coefficients ($R^2$) of allocated safety manpower as 0.853, the safety net quantity as 0.684, and the construction difficulty as 0.603 had a high explanatory power, whereas the significance probability is <0.05, and it is statistically meaningful.

Second, the HSC estimation model was developed by performing a multiple regression analysis. The developed regression model had the determinant coefficient ($R^2$) of 0.930, and the three independent variables (allocated safety manpower, safety net quantity, and construction difficulty) had a dependent variable (HSC) with a high explanatory power (suitability) of 93.0%. Additionally, the standardized coefficient turned out to be the allocated safety manpower (0.497), followed by the safety net quantity (0.338), and the construction difficulty (0.247). Particularly, it was confirmed that the factor influencing the HSC estimation the most was the allocated safety manpower, and the construction difficulty had a relatively less influence on HSC estimation.

Third, the utility of the model regarding five new projects was verified. As a result, it was confirmed that among five case sites, the sites where HSC was 2%–8% less than required, had a relatively longer construction time and complex exterior shapes. Moreover, it was confirmed that there was one site where there was a 3% surplus of HSC, because the same ratio was appropriated in proportion to the construction cost, although, it was a relatively simple construction.

Hence, through the model analyzed in this study, it is possible to estimate HSC which reflects project features when pursuing high-rise residential buildings projects. The model of this study can be utilized as a supporting data for improving the HSC-related system, and it will be developed into a more reliable model through continuous data accumulation and verification of the utility. Additionally, the developed model will be utilized in developing an optimum HSC estimation model for other constructions, such as non-residential buildings, civil engineering facilities, and plants.

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