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The post-renovation indoor environmental quality in a research institute: 3D visualization in the map

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Abstract. This study aims to evaluate and analyse how a renovation impacts occupant satisfaction through a pre-and post-occupancy evaluation with physical measurements and occupant satisfaction survey. The study was performed for the HVAC renovation of a research institute in Korea. Online occupant survey was conducted in 2021 winter before renovation and in 2022 summer after renovation. Both surveys were performed by using Korean Building Occupant Survey System (K-BOSS) which is integrated building open data including spatial information. The physical measurements through sensors were conducted simultaneously with surveys. In terms of sensor measurement, representative IEQ factors such as temperature, relative humidity, CO_2 concentration, and illuminance were measured. The surveys included three main indoor environmental quality categories such as thermal comfort, air quality, lighting environment. The measured results were analysed via T-test. As a result, the study found a statistically significant improvement with HVAC renovation about relative humidity in physical measurements and thermal comfort, air quality, overall occupant satisfaction in the survey. The results are displayed in the 3D (three dimensional) indoor map to help intuitively view gap between pre- and post-occupancy evaluation. Overall, the pre- and post-occupation evaluation survey analyses supported the beneficial effects of IEQ in the renovated building. In conclusion, the study provides a thorough examination of the effect on occupant satisfaction with IEQ of the data-driven changes collected from pre- and post-occupancy evaluation surveys.

1 Introduction

Pre- and post-occupancy evaluation can help designers develop better design solutions by identifying the impact of each building's environmental characteristics on occupant satisfaction and work productivity. Similarly, the impact of the building renovation on the occupants can also be confirmed through the pre- and post-occupancy evaluation, which can help improve the indoor environmental quality (IEQ) of occupants [1]. Therefore, studies are being conducted to improve occupant satisfaction and work productivity by confirming the correlation between renovation and IEQ through pre- and post-occupancy evaluation. For example, Asojo, A., et al. (2021) conducted an IEQ evaluation survey to check how residents perceive the existing workplace and the indoor environment of the workplace after renovation [2]. As a result of the survey, three out of four factors that were unsatisfactory in the survey conducted before the renovation were resolved in the evaluation after the renovation, confirming that the IEQ of the building was improved. Zuhaib, S., et al. (2021) investigated whether residents' IEQ changed after a partial renovation of a building [3]. As a result of the investigation, it was confirmed that the renovation of the building façade did not significantly affect the residents' IEQ evaluation. Ahrentzen, S., et al. (2016) attempted to confirm through pre- and post-occupancy evaluation whether energy renovation in elderly housing can improve IEQ, thereby improving the health and comfort of occupants [4]. As a result of the evaluation, it was confirmed that the energy uses of the building decreased after renovation, and the health and satisfaction of the elderly who are residents improved.

However, the problems of pre- and post-occupancy evaluation identified through previous studies are as follows. First, because of the time difference in performing the before-and-after evaluation, the evaluation may not be investigated by the same number of people, which may cause a problem with the reliability of the data. In addition, if it is not possible to confirm that the location of survey participants before and after renovation has changed, the use of the collected data may be limited. Finally, since most of the buildings used in the pre- and post-occupancy evaluation are residential houses or commercial facilities, a variety of buildings need to be investigated to expand the scenarios of the IEQ study.

Therefore, this study tried to expand the scenario of the IEQ study by evaluating IEQ before and after building renovation in a different way from previous studies. In this study, IEQ analysis according to renovation was compared and analysed in parallel with physical sensor measurements and qualitative occupant satisfaction survey in the public research institute building where IEQ-related research was remarkable. In

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addition, by using an new online survey system, it was confirmed that the same occupants performed evaluations before and after renovation to increase the reliability of the data. Moreover, since the study proposed a method of spatially collecting data and visualizing IEQ evaluation, such as setting comparison groups by floor with location-based questionnaires. Thus, it is considered that it will contribute greatly to the expansion of IEQ research scenarios.

2 Methodology

2.1 Study overview

In this study, an IEQ analysis framework was established to identify changes in the IEQ evaluation of occupants before and after renovation of the building. Figure 1 depicts the IEQ analysis framework used in this study. The analysis framework was designed to collect and analyse quantitative and qualitative data for four common IEQ items such as thermal comfort, air quality, lighting environment, and acoustic environment. Each IEQ item and detailed elements were based on the UC Berkeley Center for the Built Environment (CBE) survey and referenced various previous studies [2,3,5,6]. The study was conducted in a public research institute building in Korea. The building is located in a relatively low-density area that is not densely populated with surrounding buildings. The building has a total of 5 floors, and a total of 86 occupants participated in the both research before and after the renovation. The renovation target was the old HVAC system on the 5th floor, and the rest of the 1-4F units were not renovated.

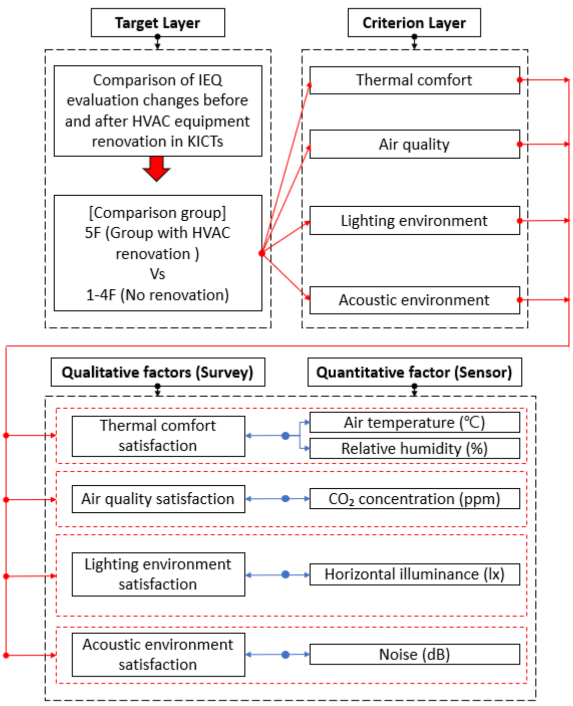


Fig. 1. Study Framework

In addition, this study used the Korean Building Occupant Survey System (K-BOSS), which can collect surveys online and visualize the measured data [7]. K-BOSS can perform a survey in conjunction with the shape and space information of a building and visualize the collected data in 3D. In this study, the collected quantitative and qualitative data were visualized through K-BOSS to more intuitively evaluate the IEQ correlation change due to the renovation. Figure 2 is an example of visually evaluating the IEQ through K-BOSS.

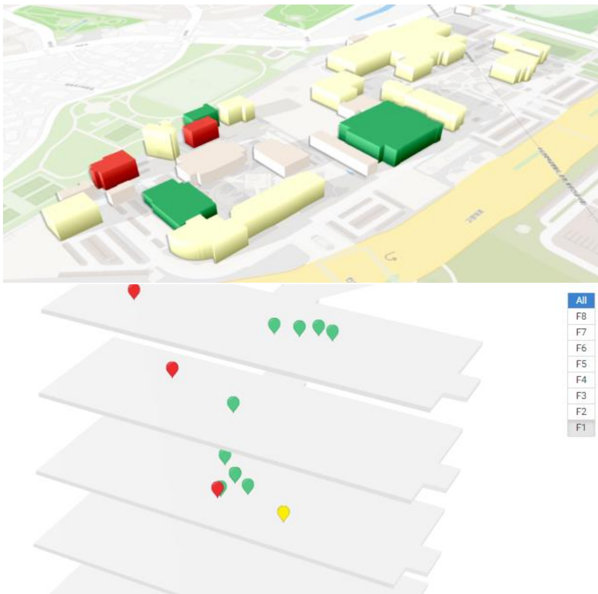


Fig. 2. Example of IEQ evaluation through K-BOSS

2.2 Quantitative evaluation

In the case of quantitative evaluation, the selected IEQ factors were evaluated by comprehensively considering the main factors identified in related studies and the factors measurable in the research institute. The IEQ factors selected for quantitative measurement in this study are as follows. First, in terms of thermal environment, indoor temperature and relative humidity, which are universal measurement IEQ factors were selected [8]. In the case of air quality, there are various IEQ factors such as fine dust and carbon monoxide. However, in this study, CO2 concentration was measured in order to use the most representative IEQ measurement factor in research area [9-12]. In the case of the lighting environment, a sensor that comprehensively measures the brightness of natural light and artificial lighting was installed to measure and analyse the brightness of the office [13,14]. In the case of the acoustic environment, it could not quantitatively have measured in this study because of concerns about security issues due to the characteristics of the public research building. To check the accuracy of the sensors, each sensor was measured for 24 hours at the same location before physical measurements.

2.3 Qualitative evaluation

In the case of qualitative evaluation, based on the IEQ questionnaire of CBE, the questionnaire was partially modified to suit the research purpose and regional characteristics through consultation with experts [6]. The occupant satisfaction on four major IEQ items such as thermal comfort, air quality, lighting environment and acoustic environment were collected and analysed through the survey. In addition, exploratory factor analysis and reliability analysis were conducted to see if the questionnaire used in this study could reliably identify the satisfaction scores evaluated in each group. Cronbach's alpha was used to verify internal consistency related to reliability. There were no problems with the other 3 IEQ items, but in the case of the acoustic environment, the reliability test score did not exceed 0.6 points, so the reliability of the items could not be secured. In addition, it was agreed to exclude data analysis on the acoustic environment in the qualitative measurement as the acoustic environment factors were not measured for security reasons even in the quantitative measurement.

3 Results

3.1 Results of quantitative evaluation

Figure 3 summarizes the distribution of temperature, relative humidity, CO2 and lighting data before and after renovation measured by the sensor. In the figure, the dotted line marked in red represents the range of standard values for each measurement factor recommended in related preceding studies [13-15]. As a result of the measurement, it was confirmed that all measured values were distributed within the relevant recommended standards, except for some of the temperature values measured at the pre-renovation period and some of the relative humidity measurements at the post-renovation period. For the measured temperature data, the data of 1-4F at pre and post periods were found to have relatively high variance values, although there was no significant difference between the data of 5F and the mean value (shown as X in Figure 3) and the median value (shown as horizon in Figure 3).

In the case of humidity data, there is a difference in data dispersion, but it was confirmed that 1-4F did not reach the recommended standards in both the pre and post periods, whereas the 5F with which HVAC improved was included in the recommended standards in the post period. In the case of humidity data, there is a difference in the data spread, but it was confirmed that 1-4F did not reach the recommended standard both before and after the renovation, while 5F with improved HVAC was included in the recommended standard in the post-renovation period. This indicates that HVAC device improvements helped improve the humidity environment at 5F.

In the case of CO2 and illuminance, all values measured at each period were within the standard range, but there was no data showing a significant difference enough to be compared.

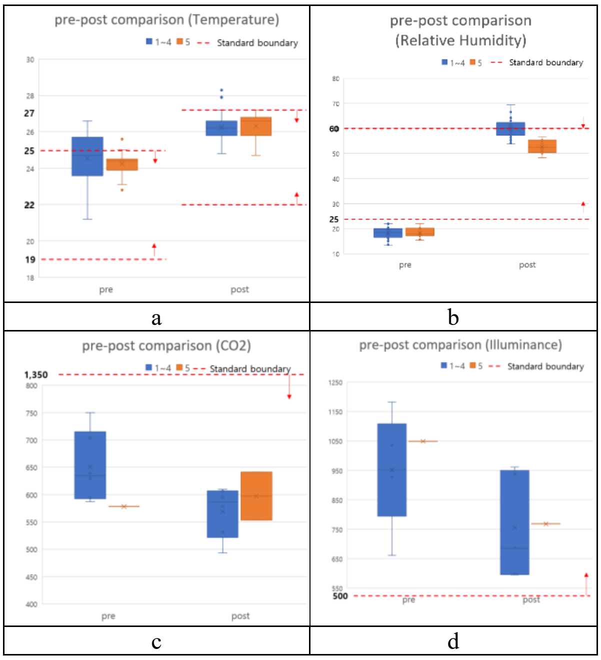


Fig. 3. Pre-, Post-renovation comparative analysis with Box-plot (a) Temperature (b) Relative Humidity, (c) CO2 concentration, (d) Illuminance

An independent sample t-test was conducted to confirm that there was a significant difference in the measured values of the IEQ variables of 1-4F and 5F according to renovation only for the data that satisfied the assumption of normality. Through the test, the differences in measured values for each group and IEQ variable in the pre-renovation period and post-renovation period were statistically analysed. As a result of the test, the analysis of the difference in quantitative measured values between each group at the pre-renovation period was temperature ($t=0.877$, $p>0.05$), relative humidity ($t=-0.019$, $p>0.05$), CO2 concentration ($t=1.050$, $p>0.05$) and illuminance ($t=-0.468$, $p>0.05$), and it was confirmed that there was no statistically significant difference. A paired-sample t-test was performed to confirm that there was a significant difference in the mean of the measured values of the IEQ variables of 1-4F and 5F according to renovation. As a result of the test, in the case of 1-4F, there was a statistically significant difference in temperature ($t=-5.493$, $p<0.001$) and relative humidity ($t=-71.139$, $p<0.001$), but CO2 concentration ($t=2.763$, $p>0.05$) and illuminance ($t=3.065$, $p>0.05$) showed no statistically significant difference. On the other hand, in the case of the 5th floor, temperature ($t=-15.932$, $p<0.001$) and relative humidity ($t=-37.001$, $p<0.001$) showed statistically significant differences, however CO2 concentration ($N=1$) and illuminance ($N=1$), it was found that it was impossible to test the difference between the measured values at the pre period and the measured values at the post period due to the insufficient number of samples.

3.2 Results of qualitative evaluation

The results of analysing qualitatively measured data through the survey are as follows. Descriptive statistical analysis was conducted to find out the mean, standard deviation, skewness and kurtosis of each individual variable. The average of individual variables was 4.73 points for thermal comfort satisfaction, 4.18 points for air quality satisfaction, 4.81 points for lighting environment satisfaction, and 4.73 points for overall satisfaction. On the other hand, the absolute skewness value of all variables was 3 or less and the absolute kurtosis value was 10 or less, confirming that there was no problem with normality, and it was confirmed that the measured data could be used for a statistical analysis.

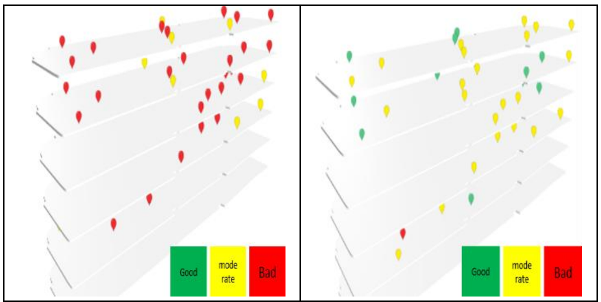
The statistical analysis was performed using the qualitative measurement values as well as data satisfying the assumption of normality. In the pre-renovation period, an independent sample t-test was conducted to confirm the significance of thermal comfort satisfaction, air quality satisfaction, lighting environment satisfaction, and overall satisfaction among the groups divided into 1-4F and 5F layers. As a result, it was analysed that thermal comfort satisfaction ($t=1.785$, $p>0.05$), air quality satisfaction ($t=0.318$, $p>0.05$), lighting environment satisfaction ($t=0.339$, $p>0.05$), and overall satisfaction ($t=-0.270$, $p>0.05$) were not statistically significant.

An independent sample t-test was conducted to compare scores for thermal comfort satisfaction, air quality satisfaction, lighting environment satisfaction, and overall satisfaction for each group measured during the post-renovation period. As a result, there was no statistically significant difference in lighting environment satisfaction ($t=0.838$, $p>0.05$), however there was a statistically significant difference in thermal comfort satisfaction ($t=-2.183$, $p<0.05$), air quality satisfaction ($t=-2.863$, $p<0.01$), and overall satisfaction ($t=-3.770$, $p<0.001$). Summarizing the IEQ variables with significant differences, it was confirmed that 5F was higher in thermal comfort satisfaction by 0.7 points, air quality satisfaction by 0.8 points, and overall satisfaction by 1.2 points than 1-4F.

A sample t-test was conducted to confirm whether the average score for each IEQ variable of 1-4F and 5F according to renovation showed a statistically significant difference. As a result, for 1F-4F, there was no statistically significant difference in thermal comfort satisfaction ($t=0.415$, $p>0.05$), air quality satisfaction ($t=0.230$, $p>0.05$), lighting environment satisfaction ($t=1.092$, $p>0.05$), and overall satisfaction ($t=1.585$, $p>0.05$). On the other hand, in the case of 5F, there was no statistically significant difference in lighting environment satisfaction ($t=-1.574$, $p>0.05$), however thermal comfort satisfaction ($t=-3.532$; $p<0.01$), air quality satisfaction ($t=-2.702$, $p<0.05$), and overall satisfaction ($t=-2.408$, $p<0.05$) were found to be statistically significant. Summarizing the IEQ items with statistically significant differences, 1.1 points for thermal comfort satisfaction, 0.85 points for air quality satisfaction, and 0.7 points for overall satisfaction increased by 1.3 points compared to the average score during the pre-renovation period.

3.3 Results of visualization

The measured quantitative and qualitative results were visualized through K-BOSS to help understanding of results. Figure 4 is a visualization of the statistically significant relative humidity among the quantitative measurement results. It was marked with reference to the standards of BS EN 16798, red colour indicates low level, yellow indicates moderate level, and green indicates high level. In the case of the pre-renovation period, it was confirmed that all floors 1-5F generally maintained the low level of relative humidity. This is the same as the relative humidity data in Figure 2. However, this study visualized the data, and it was relatively easy to check the specific location and status of relative humidity. In the case of the post-renovation period, it can be confirmed that overall sensor data are in the moderate and high levels. However, in the case of 1F, since the relative humidity of the low level appeared in some parts, it was confirmed that improvement was necessary. In addition, it was possible to check efficient quantitative evaluation data for working staff through visualization data, such as areas where the moderate level was concentrated or overall distribution.



Pre-renovation relative humidity sensor data	Post-renovation relative humidity sensor data

Fig. 4. Visualization of relative humidity data in pre- and post-renovation periods

Figure 5 visualizes the measured qualitative evaluation. Among the measured data, statistically significant thermal comfort, air quality, and overall satisfaction data were visualized. Based on the Likert 7-point scale, 1-3 points were marked in red, 4 points in yellow, and 5-7 points in green. In the case of thermal comfort, the colours of 1-4F are scattered at each stage without a clear difference between the pre and post-renovation periods. On the other hand, in the case of 5F, the difference caused by HVAC renovation can be clearly identified. In the case of air quality and overall satisfaction, the average score in the post-renovation period increased numerically in the qualitative evaluation, which was statistically significant. However, in visualization, the difference was not as clear as in thermal comfort. Nevertheless, while 5F identified fewer low levels in air quality and overall satisfaction, it was confirmed through visualization that 1-4F showed more low levels in the post-renovation period. In addition, through the recorded location data, it was possible to identify individual differences assessed at pre- and post-renovation periods.

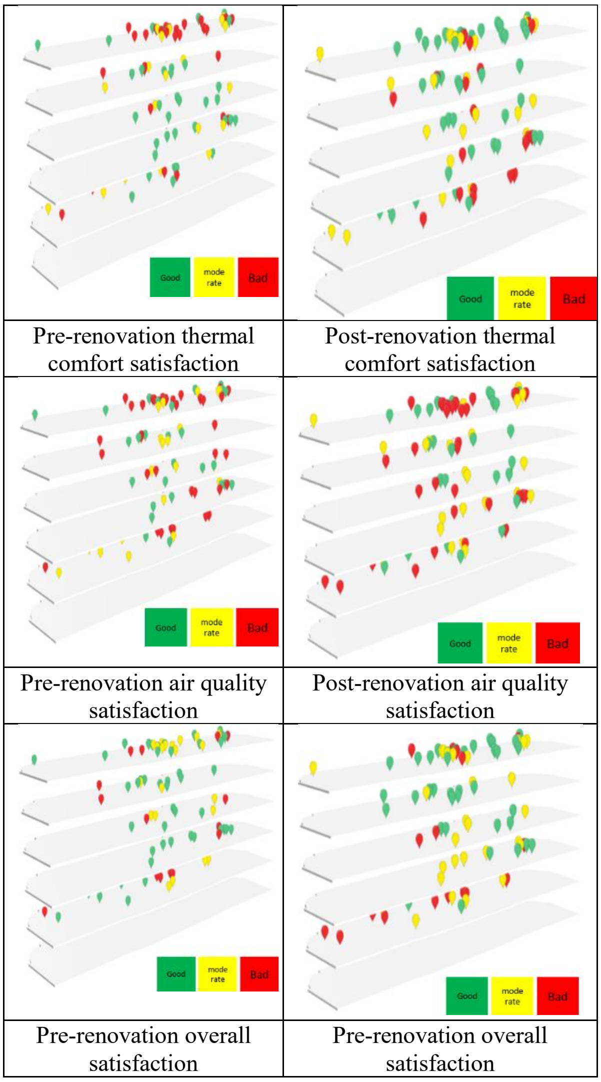


Fig. 5. Visualization of thermal comfort, air quality, and overall satisfaction in pre- and post-renovation periods

4 Discussion

4.1 Quantitative and qualitative measurement results according to HVAC renovation of the public research building

In the quantitative evaluation, among the physical measurements, the factor that showed a positive difference according to the HVAC renovation was relative humidity. In the case of relative humidity, it was confirmed that the data value measured on the 5th floor during the pre-renovation period did not reach the recommended standard, but the relative humidity data measured on the 5th floor during the post-renovation period was included in the recommended standard range. In addition, in the statistical analysis, it was confirmed that the relative humidity value of the 5th floor in the post period was significant, and it was confirmed that the statistical significance was also confirmed in the analysis of the difference in average values between pre and post-renovation. In general, as mentioned in previous studies, HVAC devices are effective in controlling and improving relative humidity in buildings [16, 17]. Therefore, as statistically verified in this study, it was confirmed that the relative humidity among the IEQ elements of public research buildings can be improved and improved through HVAC renovation.

In the case of temperature, the temperature difference between the two groups measured at pre and post periods was not statistically significant. In the case of temperature, the temperature difference between the two groups measured at pre and post periods was not statistically significant. This is presumed to be a problem caused by the existence of seasonal differences in the pre and post periods. In general, since HVAC is also involved in temperature control [16, 17], additional analysis is needed for no significant difference was identified. In the case of CO_2 concentration and illuminance, both pre and post periods were included within the recommended criteria, but statistical analysis could not be performed due to the lack of sample numbers, and it is considered that further correlation analysis is needed through additional studies.

In the qualitative evaluation, as a result of statistical analysis of the survey results during the pre-renovation period, no statistically significant differences were identified between 1-4F and 5F. This confirms that the physical difference according to the number of floors between 1-4F and 5F did not affect the qualitative evaluation values between the two groups, just like the quantitative measurement results, and means that the two groups were evaluated in an equivalent environment. According to the results of the survey conducted during the post-renovation period, the differences in measurements of thermal comfort satisfaction, air quality satisfaction, and overall satisfaction were statistically significant, excluding lighting environment. All of the significant IEQ items were found to have a higher 5F with HVAC device than the other 1-4F, which is in line with previous studies that improved the evaluation of IEQ by occupants through renovation [1,2,4]. In addition, the results of previous studies that improved the occupant satisfaction or comfort due to the renovation and operation of HVAC devices [1, 18], were also confirmed in this study conducted on public research building. Therefore, it has been statistically confirmed that improving HVAC equipment in public research building can improve the occupant satisfaction with IEQ.

4.2 IEQ correlation analysis visualization between pre and post occupant evaluation

Previous IEQ evaluation studies generally analysed the correlation between variables such as renovation and IEQ through statistical analysis. Therefore, in this study, the IEQ evaluation according to renovation was visualized using K-BOSS, an online survey system capable of spatial analysis. As a result of the visualization, in the case of thermal comfort satisfaction, which was statistically confirmed to have improved by 1.1 points, the difference between pre-renovation and post-renovation could be identified more clearly in the visualization data. It is thought that this can be used as data to improve IEQ more convincingly from the point of view of occupants in addition to researchers who evaluate IEQ. In addition, spatial data (level of satisfaction by individual and location, quality of sensor data, etc.) that could not be confirmed in general statistical data could be confirmed through visualization in this study. Therefore, individual or spatial analysis that could not be verified by the existing statistical approach is possible, and visualization of IEQ evaluation can help efficiently determine IEQ correlation with various variables by dealing with three-dimensional information. This is the originality of this study that has not been addressed in other IEQ studies, and it is expected that the scenario of IEQ research can be expanded through this result.

5 Conclusion

In this study, we expand the scenario of IEQ research by analysing the correlation of IEQ variables according to a partially renovated public research institute building in Korea. As a result of statistical analysis, it was confirmed that the both two groups (1-4F, 5F)`s physical environment was similar in the pre-renovation, and only the relative humidity was improved on 5F after the HVAC renovation. In addition, it was confirmed that thermal comfort, air quality, and overall satisfaction scores were improved in the qualitative evaluation. Additionally, the differences in quantitative and qualitative measured values between the pre and post-renovation period for each group were compared and analysed statistically. As a result of the analysis, it showed that the quantitative measurement was limited in evaluation due to the season and sensor limitations, whereas the qualitative measurement showed more diverse and specific results. Therefore, it means the survey is an essential IEQ measurement with a human sensor.

Moreover, we proposed a location-based survey system that links building information, space information, and IEQ questionnaires using low-cost open data and open source. Due to location-based data collection through the KBOSS, it was possible to intuitively assess the renovation`s effect via visualization of results that could not be seen before in statistical results. In future research, we plan to use this platform to develop an IEQ evaluation methdology using spatial information and to conduct various analyses by increasing the number of data.

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