Intelligent planning unit for the artificial intelligent based built environment focusing on human-building interaction

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ABSTRACT

The buildings’ indoor condition called “indoor environmental quality (IEQ)” has become a major goal, all IEQ elements must be maintained within a certain range for the comfort and health of the occupants. To achieve this goal, the previous studies focused on building occupants’ responses based on their activities and the changes in IEQ. Few studies, however, have comprehensively analyzed the above and reflected it in building design and operation. This study of the concept can be expressed as “human-building interaction management.” This approach is a paradigm for the healthy, sustainable, and simultaneous management of people, IEQ, and buildings. This study conducted an in-depth literature review on the above-mentioned studies. In addition, it ultimately proposed an intelligent planning unit (IPU), a new approach that can be used as a tool to apply the above human-building interaction concept to the practical design concept focusing on the planning phase. The IPU theory is designed to meet the customer expectations for the various objectives of a complex built environment. Eventually, it is expected that the proposed IPU concept will promote the spread of good health and environment-friendly buildings.

1. Introduction

As people spend more time inside buildings nowadays, comprehensive “indoor environmental quality (IEQ)” conditions have become the main target of many studies. A built environment protects the occupants from rain, snow, and wind, and provides the occupants with comfortable and satisfying thermal conditions, and human-bio-effluents-combined air (Godish 2016). This environment includes the elements of air temperature, relative humidity, air movement, ventilation, lighting, noise, etc. All these environmental elements should be maintained within specific ranges for the occupants’ comfort and health. There have been studies that analyzed the relationship between the IEQ conditions and the building occupants. The building occupants always interact with the building and its environment. For example, the building occupants exposed to a certain air temperature show specific responses until they experience “thermal comfort.” These responses can be psychological, physiological, physical, or others (Djongyang, Tchinda, and Njomo 2010).

The assessment of the IEQ condition is different even if the people are in the same building with the same environment. Some parameters are used to calculate the building occupants’ responses based on their activities and the IEQ condition changes, such as the predicted mean vote (PMV), predicted percentage of dissatisfied (PPD), and indoor air quality (IAQ) satisfaction by air temperature, relative humidity, or carbon dioxide (CO₂) concentration (Wanner et al. 1993; Fanger 1972; Hong, Kim, and Koo 2012). These parameters suggest the same calculated value in the same environment, but if individually analyzed, it may be found that they do not have the same value. The individual difference must be considered, for which reason diverse experiments were conducted and previous relevant studies were reviewed.

Traditional assessments of the values of buildings and real estate were carried out through economic or environmental assessments (Kim, Hong, and Koo 2012; Hong et al. 2015; Koo, Hong, and Park 2016; Koo et al. 2016; Jeong et al. 2018; Kim et al. 2015a, 2015b; Koo et al. 2017; Jeong et al. 2017; Ji et al. 2016; Hong et al. 2016; Park et al. 2016; Kim et al. 2016b, 2016a; Hong et al. 2013). Due to the environmental issues, however, reducing a building’s energy consumption and providing an improved IEQ are the two major issues that building professionals the world over are dealing with (Aglan, 2003; Hamilton M, Rackes A, Gurián PL, Waring MS 2016; Park and Yoon 2011; Varjo et al. 2015; Cheong et al. 2003; Ravindu et al. 2015; Lan et al. 2011; Xue, Mak,
and Ai 2016; Jaggs and Palmer 2000; Zhang, Wargocki, and Lian 2016; Kajtár and Herczeg 2012; Chen and Hsiao 2015; Cheng et al. 1995; Budd and Warhaft 1966; Sun and Zhu 2013; Mehler et al. 2009; Haapalainen et al. 2010; Carayon 1993; Fisk and Rosenfeld 1997; Worrell et al. 2003). First, according to International Energy Outlook 2016, the energy consumed by the building sector in the year 2016 accounted for about 20% of the total delivered energy consumed worldwide (Government Publications Office 2016). Second, with regard to improving the energy performance of buildings, there is a growing interest in IEQ because people have been spending more than 90% of their time inside buildings. In particular, thermal comfort, IAQ, and visual comfort are closely related to the building occupants, and each has a significant effect on the building occupants’ health. It is not easy to reduce a building’s energy consumption and provide a better IEQ at the same time. This is because the total building energy consumption tend to increase when efforts are made to maintain an acceptable IEQ level for the building occupants. Although improving the physical characteristics of a building can reduce the building’s energy consumption and improve the IEQ, these two variables vary greatly depending on the behaviors of the building occupants. The behaviors of the building occupants can be attributed to people’s responses to IEQ conditions (Wanner et al. 1993; Fanger 1972; Hong, Kim, and Koo 2012). For example, if the occupants’ psychological response is hot, the behavior triggers the building’s air conditioning system to lower the indoor temperature.

Therefore, the previous studies focusing on people’s responses based on their activities and the changes in the IEQ employed approaches that can be broadly categorized into three types: (i) approach considering the building occupants’ psychological responses; (ii) approach considering the building occupants’ physiological responses; and (iii) approach considering the building occupants’ task performance. For more details, an in-depth literature review was conducted on previous studies that could support this in section 2. Studies dealing with this concept do so in the interest of shedding light on “human-building interaction management” (refer to Figure 1).

This begins with the recognition of the human-IEQ-building interaction from a real-time perspective and from the perspective of the whole life cycle. This approach is a paradigm for the healthy, sustainable, and simultaneous management of people, IEQ, and buildings. This study conducted an in-depth literature review on the above-mentioned studies (section 2). In addition, it ultimately proposed an intelligent planning unit (IPU), a new approach that can be used as a tool to

Figure 1. Graphical abstract of human-building interaction management.
apply the above human-building interaction concept to the practical design concept focusing on the planning phase (section 3).

2. Building occupants’ responses based on their activities and the changes in the IEQ conditions

To determine the relationship between IEQ and the building occupants, three different approaches relating to human responses were employed for the analysis of the IEQ conditions. Studies aiming to determine the human responses by IEQ condition change had been conducted. Human responses are divided into two types: psychological response and physiological response. In addition, the activities of the building occupants under certain IEQ conditions were verified as the last approach relating to the human response. Therefore, the psychological and physiological responses as well as the building occupants’ activities were generally reviewed.

2.1. Approach considering the building occupants’ psychological responses

The psychological response, a human response, is hard to define precisely. This is because psychological responses can be observed differently for each individual when the physical environment changes. Also, the psychological response of the same person may be different depending on the surrounding environment at the time. Many types of research analyzing psychological responses require a time-consuming process. Diverse indices of psychological responses could be found, however, throughout literature reviews. The studies considering the psychological response are divided into four categories according to their goal (refer to Table 1): (i) those dealing with the indoor air pollutant factors; (ii) those dealing with the indoor climate factors; (iii) those dealing with both indoor factors; and (iv) the activities of the building occupants under a certain IEQ condition.

2.1.1. Building occupants’ psychological responses to indoor air pollutant factors

The building occupants’ IAQ satisfaction was analyzed with the indoor air pollutant factors, mainly the CO₂ concentration (Aglan 2003; Hamilton et al. 2016; Park and Yoon 2011; Daisey, Angell, and Apte 2003; Kim et al. 2016c; Vehviläinen et al. 2016). The CO₂ concentration is deeply related to ventilation and humans because CO₂ is emitted mainly through the subjects’ metabolic processes and equipment use. Aglan (2003) developed and assessed a CO₂ concentration prediction model that would improve the building’s IAQ. An appropriate ventilation rate was suggested according to the maximum CO₂ concentration by time. Hamilton et al. (Hamilton et al. 2016) used ventilation and filtration as analysis elements and analyzed these with their benefit of better IAQ on 112 stakeholders through questionnaire surveys. Majority of the stakeholders expressed dissent with regard to the ventilation and filtration effects and the benefits of better IAQ. They refused to pay for improving the IAQ, showing indifference towards the importance of ventilation. Hedge (1996) announced that because many IAQ hazards cannot be directly measured, the building occupants’ psychological responses play a huge role in avoiding such hazards. The itchiness of the skin and the urge to cough, two sensory processes that influence the perception of the IAQ, cannot be neglected.

Wolkoff and Nielsen (2001) used volatile organic compounds (VOCs) to evaluate the perceived air quality and argued that the classic VOCs defined by the World Health Organization (WHO) are not enough for

| Factors affecting building occupants | Unit | Reference | Year |
|--------------------------------------|------|-----------|------|
| Indoor air pollutant factor | CO₂ | Aglan (2003) | 2003 |
| | | Hamilton et al. (2016) | 2015 |
| | | Park and Yoon (2011) | 2011 |
| | | Daisey, Angell, and Apte (2003) | 2003 |
| | | Kim et al. (2016c) | 2016 |
| | | Vehviläinen et al. (2016) | 2016 |
| | | Hummelgaard et al. (2007) | 2007 |
| VOCs | | Hedge (1996) | 1996 |
| | | Wolkoff and Nielsen (2001) | 2001 |
| Indoor climate factor temperature | °C (°F) | Fanger (1972) | 1976 |
| | humidity (%) | Varjo et al. (2015) | 2015 |
| | air velocity (m/s) | Cheong et al. (2003) | 2003 |
| | | Ravindu et al. (2015) | 2015 |
| | | Tham (2004) | 2004 |
| Both Indoor air pollutant factor and Indoor climate factor | | Wagner et al. (2007) | 2007 |
| | | Auliciems and Sokolay (1997) | 1997 |
| | | Luo et al. (2016) | 2016 |
| | | Verheyen et al. (2011) | 2011 |
| | | Lan et al. (2011) | 2011 |
| | | Xue, Mak, and Ai (2016) | 2016 |
| | | Jaggs and Palmer (2000) | 2000 |
| | | Reynolds et al. (2001) | 2001 |
| | | Ivanov (2016) | 2016 |
| | | Tanabe et al. (2013) | 2013 |
| | | Buratti and Ricciardi (2009) | 2009 |
| | | Kotopoulouas and Nikolopoulos (2016) | 2016 |
| | | Maua et al. (2016) | 2015 |
| | | Sicurella and Colamasta (2015) | 2015 |
| | | Heinzerling et al. (2013) | 2013 |
| | | Moschandreas and Sofouglou (2004) | 2004 |
| Activities of the occupants | | Auliciems and Sokolay (1997) | 1997 |
| | | Luo et al. (2016) | 2016 |
| | | Yun et al. (2014) | 2014 |
| | | Zomorodian, Tahsildoust, and Hafezi (2016) | 2016 |
evaluation purposes, and that a broader analytical window of VOCs should be used. Hummelgaard et al. (2007) recorded the subject building occupants’ responses and the IEQ characteristics in their study to compare five mechanically ventilated and four naturally ventilated office buildings. The results showed that even though the CO₂ concentration was fluctuating and was sometimes higher in the naturally ventilated office buildings, the psychological satisfaction of the naturally ventilated office buildings’ occupants was higher than that of the mechanically ventilated office buildings’ occupants. This result signifies the existence of another possible determinant of the building occupants’ IAQ satisfaction.

2.1.2. Building occupants’ psychological responses to indoor climate factors

The building occupants’ thermal comfort was analyzed with the indoor climate factors, mainly based on Fanger’s model (Fanger 1972; Varjo et al. 2015; Cheong et al. 2003; Ravindu et al. 2015; Tham 2004; Wagner et al. 2007; Auliciems and Szokolay 1997; Luo et al. 2016; Verheyen et al. 2011). Fanger’s model uses four indoor climate factors (operative temperature, relative humidity, air velocity, and global temperature) and two personal factors (clothing insulation and metabolic rate) (Auliciems and Szokolay 1997; Luo et al. 2016) to calculate the PMV and the PPD, which indicate the level of thermal comfort of the building occupants. International standard organizations refer to this PMV-PPD model as the standard (Luo et al. 2016; Verheyen et al. 2011).

Both ISO 7730 and ASHRAE 55 define the operative temperature range for thermal comfort based on the indoor climate factors that derive the desired level of thermal comfort. In ASHRAE 55, the recommended operative temperature range (the thermal condition considered acceptable by more than 80% of the building occupants) is 18.6–30.2°C for secondary activities (Zhang 2015). This recommended range was derived based on the thermal comfort indices (PMV and PPD), as knowledge generalized by Fanger. The PMV-PPD indices, however, were developed through a questionnaire survey on the thermal responses of people who had been acclimatized to the IEQ. This could be accounted for by introducing an expectation index (Fanger and Toftum 2002). Various international standards for thermal comfort are suggested, such as ISO 7730 (ISO, EN. 7730: 2005), EN 15251 (Olesen 2012), ASHRAE 55 (STANDARD, ASHRAE 2010), and GB/T 50785 (Luo et al. 2016). ASHRAE 55 is utilized as a standard that can measure the thermal sensation of the building occupants by using the PMV-PPD model of thermal comfort based on Fanger’s model in the natural ventilation environmental space. After the selection of the human comfort range for the first time in 1941, ASHRAE revised the comfort range seven times up to ASHRAE 2010. The thermal comfort standard of ASHRAE 55 is divided into PPD 10 and 20%. Accordingly, the presented PMV is ±0.5 and ±0.85 (Luo et al. 2016; Zhang 2015; De Vecchi et al. 2015).

- ISO 7730 is utilized as a standard to measure the thermal environment felt by the building occupants in the same way as in ASHRAE. ISO7730 is divided into three categories to estimate the thermal comfort of the building occupants. The PMV standards are presented from a minimum of ±0.2 in category I to a maximum of ±0.7 in category III. Therefore, the comfort operative temperature range from the tolerance standard is presented as 17–31°C (International Organization for Standardization 2005).

- European-standard EN 15251 presents standards for the thermal environment in a naturally ventilated space. EN 15251 is divided into four categories. Category I has the strictest thermal comfort standards, and accordingly, the operative temperature range is 20.5–31.2°C (Zhang 2015; Olesen 2012).

- Chinese standard GB/T 50785 was released by the Ministry of Housing and Urban-Rural Development in May 2012. GB/T 50785 consists of three categories on the thermal comfort of building occupants. Category I presents standards on the building occupants’ 90% satisfaction level. Category II provides standards on the building occupants’ 75% satisfaction level. Finally, category III provides standards that are unacceptable by the building occupants (Zhang 2015; Li et al. 2014).

The questionnaire survey is the most traditional and formal way to determine the level of thermal comfort of building occupants under extensive indoor climate and personal factors. Cheong et al. (ISO, EN. 7730: 2005) conducted a questionnaire survey on 189 subjects, measuring their thermal comfort level in an air-conditioned lecture room. According to the questionnaire survey results, the experiment subjects appraised the PMV as −0.93 and the PPD as 20.6%, meaning one out of five subjects felt unpleasant and slightly cool under the relevant environment. The study recommended that the indoor air temperature be raised to about 26°C for the occupants’ thermal comfort. Ning et al. (2016) employed a similar approach, analyzing climate change with the indoor climate factors and the thermal comfort level of the building occupants in China. Similar to other studies, it conducted a questionnaire survey on the thermal comfort level of the experiment subjects from autumn to spring. The PMV and the mean thermal sensation vote (TSV) were compared, and it was found that the calculated PMV was lower than the actual thermal comfort of the experiment subjects. This result
signified the existence of other possible determinants of the thermal comfort level of building occupants.

2.1.3. Building occupants’ psychological responses to both indoor factors

Both psychological responses of IAQ satisfaction and thermal comfort of building occupants were analyzed with the IEQ conditions (Lan et al. 2011; Xue, Mak, and Ai 2016; Jaggs and Palmer 2000; Reynolds et al. 2001; Ivanov 2016; Tanabe et al. 2013; Buratti and Ricciardi 2009; Kotopouleas and Nikolopoulou 2016; Maula et al. 2016; Sicurella and Colamesta 2015). The indoor air pollutant factors, indoor climate factors, and other possible factors, such as the acoustics and lighting, were considered. There have been some studies that analyzed diverse psychological responses to the IEQ conditions. Xue, Mak, and Ai (2016) used a questionnaire survey to determine the overall environmental satisfaction of about 480 residents of high-rise residential buildings with the IEQ conditions in their respective buildings. Reynolds et al. (2001) concentrated on various other IEQ parameters – indoor pollutant factors (CO₂ concentration, acetaldehyde, VOCs, and formaldehyde), indoor climate factors (operative temperature and relative humidity), lighting, and noise – in six large office buildings. The noticeable results were that the IEQ parameters were correlated with one another and all the parameters were related to the building occupants’ psychological responses. Ivanov (2016) surveyed untrained and unprepared occupants of a small lecture room and analyzed both the IAQ and the thermal comfort, but he obtained uncertain results due to the low questionnaire response rate. There have been few studies that simply combined the building occupants’ psychological responses to the indoor air pollutants and indoor climate factors. Heinzerling et al. (2013) conducted a literature review on the weighting and classification of IEQ and found that it is difficult to integrate the results of their review due to the absence of specific relevant standards or criteria. Moschandreas and Sofuoğlu (2004) calculated the indoor environmental index of both indoor discomfort and indoor air pollution using the rank correlation coefficient, but they considered only the building occupants’ psychological responses to the building temperature and humidity, and numerically compared the indoor air pollutant factors to the demarcation of each pollutant variable.

2.1.4. Building occupants’ psychological responses to their own activities

Finally, the building occupants’ psychological responses differed by building occupant activity even under the same IEQ condition (Auliciems and Szokolay 1997; Luo et al. 2016; Yun et al. 2014; Zomorodian, Tahsildost, and Hafezi 2016). Few studies have dealt with this complicated subject in an in-depth way. Luo et al. (2016) found different TSVs on the same IEQ condition. The only difference was that the building occupants with better TSV results were informed that they could control the indoor air temperature when such temperature in fact did not really change at all. The experiment result that the building occupants’ psychological responses changed without a change in the actual IEQ condition and with only the possibility of the building occupants’ control of such condition is crucial. The building occupants’ belief that they can change the IEQ condition to a suitable one can affect their psychological responses.

2.2. Approach considering the building occupants’ physiological responses

If there are psychological responses of occupants, there should be occupants’ physiological responses based on their activities and IEQ condition too. The physical status (e.g., physical health) can be analyzed based on the physiological responses. Recent technological advances enabled the measurement of the real-time monitoring data on physiological responses. As the physiological responses to the IEQ condition can indicate the maintenance of homeostasis against external stimuli, in this study, such responses were used as the occupant health index (Zhang, Wargocki, and Liu 2016; Kajtár and Herczeg 2012; Chen and Hsiao 2015; Cheng et al. 1995; Budd and Warhaft 1966; Sun and Zhu 2013). The previous studies that used building occupants’ physiological responses were also divided into three categories: (i) those that dealt with building occupants’ physiological responses to the indoor air pollutant factors; (ii) those that dealt with building occupants’ physiological responses to the indoor climate factors; and (iii) those that dealt with building occupants’ physiological responses to their own activities (refer to Table 2). It was hard to find studies that dealt with both indoor factors combined.

2.2.1. Building occupants’ physiological responses to the indoor air pollutant factors

The building occupants’ physiological responses to the indoor air pollutant factors were analyzed. As mentioned earlier, the CO₂ concentration was mainly used as an indoor air pollutant factor. Diverse physiological responses like the blood pressure, heart rate, and respiratory rate were used for the analysis, along with the indoor CO₂ concentration change. Zhang, Wargocki, and Liu (2016) found end-tidal CO₂ increase by a high CO₂ concentration in a climate chamber. Kajtár and Herczeg (2012) found that the diastolic blood pressure and heart rate was increased by a high (near 300 ppm) CO₂ concentration.

Chen and Hsiao (2015) found that the increase in CO₂ concentration led to respiratory change and increased
Table 2. Building occupants’ physiological responses and activities, and IEQ condition.

| Factors affecting building occupants | Unit | Reference | Year |
|--------------------------------------|------|-----------|------|
| Indoor air pollutant factor          | CO₂  | Zhang, Wargocki, and Lian (2016) | 2016 |
|                                      |      | Kajtár and Herczeg (2012) | 2012 |
|                                      |      | Chen and Hsiao (2015) | 2015 |
|                                      |      | Apte, Fisk, and Daisey (2000) | 2000 |
|                                      |      | Vehviläinen et al. (2016) | 2016 |
|                                      |      | Zhang, Wargocki, and Lian (2017) | 2017 |
| Fine particulate (PM2.5, PM10)       |       | Linn et al. (1999) | 1999 |
|                                      |       | Zanobetti et al. (2004) | 2004 |
|                                      |       | Choi et al. (2007) | 2007 |
| Indoor climate factor                |      | Cheng et al. (1995) | 1995 |
| temperature (°C, °F)                 |      | Budd and Warhaft (1966) | 1966 |
| humidity (%)                         |      | Sun and Zhu (2013) | 2013 |
| air velocity (m/s)                   |      | Mäkinen et al. (2006) | 2006 |
| Work stress                          |      | Toftum, Jørgensen, and Fanger (1998) | 1998 |
|                                      |      | Tham and Willem (2010) | 2010 |
|                                      |      | Wyndham et al. (1964) | 1964 |
|                                      |      | Høppe et al. (2000) | 2000 |
|                                      |      | Frank et al. (1999) | 1999 |
|                                      |      | Collins et al. (1983) | 1983 |
|                                      |      | Mehler et al. (2000) | 2000 |
|                                      |      | Callister, Suwano, and Seals (1992) | 1992 |
|                                      |      | Heidbreder et al. (1982) | 1982 |
|                                      |      | Ettema and Ziehuis (1971) | 1971 |
|                                      |      | Lenneman, Shelley, and Backs (2005) | 2005 |
|                                      |      | Thackray and Pearson (1968) | 1968 |
|                                      |      | Philips et al. (2006) | 2006 |
|                                      |      | Zeier, Brauchli, and Joller-Jemelka (1996) | 1996 |
|                                      |      | Vrijkotte, Van Doomen, and De Geus (2000) | 2000 |

systolic and diastolic blood pressures of 30 subjects with severe chronic obstructive lung disease. Both blood pressures were found not related to the PM levels, but other studies obtained opposite results. Zanobetti et al. (2004) confirmed diastolic and systolic blood pressures and heart rate increments by PM2.5 level increment. Choi et al. (2007) also found that the systolic and diastolic blood pressures increased with high PM10 levels. Caruana-Montaldo, Gleeson, and Zwillich (2000) likewise found that an increased indoor CO₂ concentration could lead to respiration rate, body temperature, and metabolism increase.

2.2.2. Building occupants’ physiological responses to the indoor climate factors

The building occupants’ physiological responses to the indoor climate factors were also analyzed. Cheng et al. (1995) investigated if the mean skin temperature and core temperature had a linear relationship with each other, causing shivering in a cold environment, and found affirmative results. Budd and Warhaft (1966), Sun and Zhu (2013), and Mäkinen et al. (2006) analyzed the changes in the blood pressure with thermal change and found that operative temperature increase leads to blood pressure decrease. Toftum, Jørgensen, and Fanger (1998) observed the increase in skin humidity due to the increase of the operative temperature and suggested the new skin humidity model for sedentary, thermal-neutral persons. Tham and Willem (2010) conducted an experiment with 96 young adults to analyze the room air temperature and the subjects’ mental alertness through their physiological responses, and found an increase in α-amylase at the moderately cold temperature of 20°C, inducing nervous system activation. Wyndham et al. (1964) investigated the gender difference in the physiological response of sweat over skin under thermal change, and the study results showed that the female subjects produced less sweat than the male subjects did. Höppe et al. (2000) researched on the relationship between clothing and the human response of skin humidity, and concluded that increased temperature leads to the increment of skin humidity. Frank et al. (1999) observed that the body core and skin surface temperatures are critically affected by core cooling; that is, both temperatures decrease with core cooling. Collins et al. (1985) also analyzed the mean deep body temperature and systolic and diastolic blood pressures when the study subjects were exposed to 6°C air, and the study results showed a body temperature decrease and a blood pressure increase.

2.2.3. Building occupants’ physiological responses to their own activities

Unlike the building occupants’ psychological responses, there is a term for the building occupants’ activities that affect their own physiological responses.
Office work or the stress accompanying work causes work stress on the part of the building occupants. Work stress was analyzed with the physiological responses in other previous studies, as activities of the building occupants. The types of stress of the building occupants are diverse, but in an office building, job stress, work stress, office work, and cognitive tasks can be defined (Mehler et al. 2009; Haapalainen et al. 2010; Carayon 1993). Under the same IEQ conditions, the physiological response can change due to stress that affects the autonomic nervous system, and the excitement of the sympathetic nervous system causes various cardiovascular responses, which are related to physiological responses (Callister, Suwarno, and Seals 1992; Heidbreder et al. 1982). Ettema and Zielhuis (1971) and Fredericks et al. (2005) studied the heart rate and the blood pressure (which is related to cardiovascular responses) under a mental workload. The experiments revealed that the mental workload increases the heart rate and blood pressure. Lenneman, Shelley, and Backs (2005) and Thackray and Pearson (1968) also reported that in their study, the subjects’ heart rate was increased by the subjects’ stress. Mehler et al. (2009) discovered an increased heart rate and increased skin conductivity by office workload. Phillips et al. (2006) and Zeier, Brauchli, and Joller-Jemelka (1996) used salivary secretory immunoglobulin A (sIgA), an indicator of the status of the immune system, as the main physiological response under high stress conditions. As a result, the highly negative stress decreased the sIgA, meaning there was a diminution of the immune system’s performance. Vrijikotte, Van Doornen, and De Geus (2000) announced the risk of developing cardiovascular disease from work stress, and monitored the ambulatory blood pressure, heart rate, and heart rate variability to analyze the results of a diverse combination of high and low work stress. The study results showed that work stress is mediated by systolic blood pressure increase.

### 2.3. Approach considering the building occupants’ task performance

As in this approach, the psychological and physiological responses of the building occupants to the IEQ condition and their own activities are analyzed, the IEQ condition and the occupants’ task performance should also be analyzed. In this study, the activities of office occupants were measured by task performance. The change in the task performance with IEQ condition change was analyzed. The indoor air pollutant and indoor climate factors are the two IEQ conditions that were studied (refer to Table 3).

### 2.3.1. Building occupants’ task performance to the indoor air pollutant factors

According to the previous relevant studies, the indoor air pollutant factors are related to human health, especially to infection, allergies, and other complex symptoms, like those falling under the so-called “sick building syndrome,” and chemical and microbiological indoor air pollution lead to loss of productivity (Fisk and Rosenfeld 1997; Worrell et al. 2003).

As mentioned earlier, the CO₂ concentration is related to the ventilation rate and is one of the common research subjects on the indoor air pollutant factors. The previous relevant studies verified that the CO₂ concentration is closely related to the building occupants’ task performance (Bako-Biró et al. 2002; Fromme et al. 2007; Lagercrantz and Sundell 2000; Lee et al. 2012; Higgins et al. 2005; Mendell et al. 2016; Myrhvold, Olsen, and Lauridsen 1996; Nordström, Norbäck, and Akselsson 1994; Persily 2015; Satish et al. 2012; Seppänen and Fisk 2004; Wargocki et al. 2002; Wargocki and Wion 2007; Wargocki, Wion, and Fanger 2000; Wargocki et al. 1999). Myrhvold, Olsen, and Lauridsen (1996) analyzed the occupants’ cognitive abilities and the average CO₂ concentration in 22 classrooms. In the experiment, a concentration test and a self-questionnaire survey were used to determine the status of the subjects, and the reaction time with the PC for 30 minutes was measured. The results showed that the concentration of the pupils decreased with a higher CO₂ concentration. Bakó-Biró et al. (2012) analyzed ventilation and the building occupants’ task performance. Two hundred subjects in two classrooms participated in the test, and their cognitive performance was measured with

### Table 3. Building occupants’ task performance to IEQ condition.

| Factors affecting building occupants | Unit          | Reference                          | Year |
|--------------------------------------|---------------|------------------------------------|------|
| Indoor air pollutant factor          | CO₂           | Fisk and Rosenfeld (1997)          | 1997 |
|                                      |               | Worrell et al. (2003)              | 2003 |
|                                      |               | Myrhvold, Olsen, and Lauridsen (1996) | 1996 |
|                                      |               | Bako-Biró et al. (2012)            | 2012 |
|                                      |               | Shendell et al. (2003)             | 2008 |
|                                      | O₃/VOC/NO₂/Fine particulate (PM2.5) | Gatto et al. (2014)               | 2014 |
|                                      |              | Clements-Croome et al. (2008)      | 2008 |
| Indoor climate factor               | temperature °C (°F) | Lan et al. (2011)                  | 2011 |
|                                      | humidity (%)  | Hummelgaard et al. (2007)          | 2007 |
|                                      | air velocity (m/s) | Wagner et al. (2007)               | 2007 |
|                                      |               | Myrhvold et al. (2004)             | 2004 |
|                                      |               | Konesen and Tan (2004)             | 2004 |
|                                      |               | Pilcher, Nadler, and Busch (2002)  | 2002 |
|                                      |               | Fang et al. (2004)                 | 2004 |
|                                      |               | Seppänen, Fisk, and Lei (2006a)    | 2006 |
|                                      |               | Zhang et al. (2010)                | 2010 |
|                                      |               | Seppänen, Fisk, and Lei (2006b)    | 2006 |
|                                      |               | Cui et al. (2013)                  | 2013 |
nine tests administered by computer software. With outdoor air ventilation, the subjects’ cognitive ability or short-term memory statistically increased. Shendell et al. (2003) analyzed the attendance of different pupils by the indoor and outdoor CO₂ concentrations in 22 schools, and the results showed that when the CO₂ concentration exceeded 1000 ppm, the average pupil attendance was reduced by 0.5–0.9%. Other air pollutant factors also affect the building occupants’ task performance and cognitive abilities. Gatto et al. (2014) analyzed the ozone, PM2.5, and NO₂ concentrations and the building occupants’ cognitive abilities. Their experiment with almost 1,500 adults showed that increasing exposure to PM2.5 led to lower verbal learning. Clements-Croome et al. (2008) did not aim at specific air pollutant factors but physically measured the CO₂ concentration and VOCs; instead, they investigated the ventilation rate in the classrooms vis-à-vis the pupils’ cognitive performance.

2.3.2. Building occupants’ task performance to the indoor climate factors

There is yet no definite, clear mechanism of how the indoor climate factors affect the activities of the building occupants as well as their task performance (Willem 2006). Researchers have found, however, that the cognitive processing of IEQ changes causes various combinations of human physical, psychological, and physiological responses (Chamberlain and Jordan 2012; Kim and Paulos 2010), but the result arrived at by other studies is clear: the indoor climate factors of indoor temperature and relative humidity affect the task performance of the building occupants (Akimoto et al. 2010; Azarbayjani, Brentrup, and Cox 2014; Hunn and Bochat 2015; Mak and Lui 2012; Niemelä et al. 2002; Roelofsen 2002; Schellen et al. 2010; Wiik 2011). In addition, the indoor temperature has been known to greatly affect human thermal comfort and productivity (Wyon 2004). In a cold indoor environment, a negative effect on the building occupants’ task performance was observed (Lan et al. 2011; Hummelgaard et al. 2007; Bakó-Biró et al. 2012; Kosonen and Tan 2004; Pilcher, Nadler, and Busch 2002; Fang et al. 2004). Fang et al. (2004) analyzed the indoor temperature and relative humidity vis-à-vis the building occupants’ task performance; the study subjects showed the best problem-solving abilities in a slightly cool temperature. In other studies, at a 22°C indoor temperature, the building occupants showed the best productivity. As the operative temperature increased, the productivity decreased (Seppanen, Fisk, and Lei 2006a). Zhang et al. (2010) used their own thermal comfort model and task-ambient condition system and checked the thermal comfort, perceived air quality, and task performance of the building occupants through 90 tests. The building occupants performed better in Sudoku and math with the task-ambient condition system compared to the neutral condition. Math was performed better in cool conditions while Sudoku was performed better in warm conditions. Seppanen, Fisk, and Lei (2006b) analyzed office-type tasks like text processing, simple calculations, telephone customer service, and similar other works vis-à-vis the room temperature. The task performance decreased when the room temperature was 30°C. Cui et al. (2013) found that the slightly cool to neutral temperatures of 22–26°C were optimal for learning performance.

3. IPU for the artificial intelligent based built environment considering the impact of the indoor air pollutants and indoor climate factors

The building is one of the main agents controlling the indoor environment. To control the IEQ condition, modern office buildings use diverse equipment and systems. From air-conditioning to ventilation, a building consumes a considerable amount of energy to maintain the best IEQ condition, which means that energy consumption can be used as an index of the building status. In this study, both the indoor air pollutant and indoor climate factors were analyzed along with building energy consumption. IPU, a new approach that can be used as a tool to apply the above human-building interaction concept to the practical design concept focusing on the planning phase, was proposed (Hastak and Koo 2016a). The theory of an IPU is designed to (1) enable the complex built environment system to be more intelligent; (2) standardize the complex physical entities and processes at a modular scale; (3) accumulate the knowledge at different levels of complexity for IPU refinement and control; and (4) provide the decision-makers with timely and accurate information for better decision-making (Hastak and Koo 2016b). The presented IPU case scenarios illustrate the IPU strategy, design, replication, combination, interaction, and refinement aspects with different levels of complexity in the built environment.

3.1. IPU considering the indoor air pollutant factors and energy consumption

As mentioned earlier, IAQ is affected by indoor air pollutants like the CO₂ concentration. Other indoor air pollutants include VOCs and fine particulate, which are notable pollutants (refer to Table 4). The indoor air pollutant factors are related to the ventilation performance. To maintain an acceptable condition for almost 90% of the building occupants, the CO₂ concentration should be maintained at around 1000 ppm (Mui and Wong 2007). Fine particulate (including PM10 and PM2.5) and VOCs can also be used as
substitutional indicators of the required ventilation for an acceptable IAQ (Rea 2000; Chung and Burnett 1996; Mui and Wong 2006; Ayr et al. 2003; Wong and Mui 2009). The main building energy that was used in this study for analysis with the indoor air pollutant factors was thermal energy consumption. Takeda et al. (Takeda et al. 2004) compared and developed a ventilation system with a phase change material utilizing thermal energy storage, and concluded that the cooling load could also be reduced by the ventilation system.

A previous research concluded that the CO$_2$ concentration as well as the thermal energy consumption, which is mainly related to the CO$_2$ concentration, affects the ventilation in air-conditioned offices (Mui and Wong 2007). When the indoor CO$_2$ concentration increased from 1,000 to 1,200 ppm, 30% thermal energy reduction was estimated for the air-conditioned office buildings, but the occupant acceptability decreased. Rijal et al. (Rijal et al. 2007) used field surveys to predict the thermal comfort and energy use with the opened window. The results showed that the number of opened windows determines the levels of indoor air pollutant factors. Also, a decrease in CO$_2$ concentration led to a 50% increase in additional thermal energy (Mui, Wong, and Law 2007). Hien et al. (2005) simulated both the single- and double-glazed façade and concluded that to minimize the building energy consumption, the double-glazed façade with natural ventilation was the best option for use.

**Table 4. IPU for the built environment and IEQ condition.**

| Indoor air pollutant factor and energy consumption | CO$_2$ | Reference | Year |
|--------------------------------------------------|--------|-----------|------|
| Mui and Wong (2007) | - | 2007 |
| Mui, Wong, and Law (2007) | Rea (2000) | 2000 |
| Fine particulate | Chung and Burnett (1996) | 1996 |
| Mui and Wong (2006) | Ayr et al. (2003) | 2003 |
| Wong and Mui (2009) | Takeda et al. (2004) | 2004 |

**Indoor climate factor and energy consumption**

| Temperature (°C) | Reference | Year |
|------------------|-----------|------|
| Brager and De Dear (1998) | 1998 |
| De Dear and Brager (1998) | 1999 |
| Imanari, Omori, and Bogaki (1999) | 2014 |
| Yang, Yan, and Lam (2014) | 1997 |
| Lam, Hui, and Chan (1997) | 1998 |

**3.2. IPU considering indoor climate factors and energy consumption**

As mentioned earlier, the thermal comfort can be calculated as PMV by indoor climate factors like the indoor temperature and humidity (refer to Table 4). Maintaining the indoor climate factors is fundamental to air-conditioned office buildings. The specific indoor climate factors that increase the building occupants’ thermal comfort are different in many literature reviews, and they also affect the building energy consumption. For thermal comfort, Brager and De Dear (1998) reported that the distinction between the thermal comfort responses in air-conditioned vs. naturally ventilated buildings most likely results from a combination of the past thermal history of the buildings and the differences in the levels of perceived control. They reported that even though air-conditioned offices were exposed to the “recommended acceptable state,” thermal discomfort was reported (De Dear and Brager 1998). For energy consumption, Imanari, Omori, and Bogaki (1999) compared the thermal comfort, energy consumption, and cost of the ceiling panel system and the conventional air-conditioning system. Through questionnaire surveys, a simulation was conducted, and a 10% energy consumption reduction was found. Yang, Yan, and Lam (2014) reviewed the thermal comfort and building energy consumption and concluded that a higher or wider indoor temperature range leads to a lower cooling load and energy consumption, but further research for the social norm should be considered. Similarly, just by increasing the indoor air temperature set point by 1°C, nearly 4% annual thermal energy savings can be achieved (Lam, Hui, and Chan 1997). If the thermal comfort is considered, to achieve the thermal comfort of the building occupants, nearly 40% of the overall building thermal energy is used by the heat gains through the building envelope (Chow and Wong 1998).

**3.3. IPU for the artificial intelligent based built environment**

The level and scale of the IPU are configured as shown in Figure 2. As the IPU’s scale becomes smaller, the IPU’s number increases. The IPUs of the corresponding scale from nanoparticles to component, space, and global scale are accumulated to form the next-scale IPU.

By monitoring, diagnosing, and retrofitting buildings from the perspective of the full building life cycle, the previous studies aimed to achieve the construction of green buildings. There were clear
differences, however, between the predicted and actual building performances in terms of energy and IEQ. The main reason for such difference is the “human factor”: how the building occupants psychologically and physiologically respond to and operate the building. Each scale of IPU can consider the “human factor” based on the real-time data acquired from three crucial factors: human health, IEQ, and building energy. These can be referred to as requirement-key performance indicators, and the IPU can be finally designed considering the cost, environment, and energy as the target key performance indicators.

The IPU can be used as a general tool to apply the above human-building interaction concept to the practical building design. Based on the issues covered in section 2 and section 3, the factors affecting building occupants can be applied to the requirement-key performance indicators in the IPU process. The requirement-key performance indicators can be established according to each project such as indoor air pollutant, indoor climate and occupants’ activities. To show a design example through the IPU, a four-story building was selected as the target facility, and the detailed description is as follows. In the process of constructing a four-story sports center including one basement, the third-floor room is designed as follows. The rooms consist of a lecture room, an office, a gymnasium, etc. Each room can be designed according to the requirement-key performance indicators. In the case of designing according to the indoor air pollutants, indoor climate factors, and building occupants’ task performance, among the various requirement-key performance indicators, IPU can be named as shown in Figure 3.

The named IPU can be designed with cost, environment, and energy as the target key performance indicators according to the level of the requirement-key performance indicator defined above (refer to Figure 4). The final decision-maker can select the final IPU scenario based on the requirement-key performance indicator and the target-key performance indicator. This choice of room-level IPUs can lead to the cumulative total building design. That is, it can be applied to all scales of built environments. For the future research,

**Figure 2.** Scale and number of IPUs.

**Figure 3.** Designing a sports center based on IPU.
it is necessary to deal with human health based on the IPU.

- Quantification of environmental quality and development of an environment-combined index: In the previous studies, the IEQ score can estimate the IEQ based on the building characteristics and human behavior (Kim et al. 2017a, 2017b, 2018; Hong, Kim, and Lee 2018). To minimize the generation of environmental pollutants, eco-friendly building materials and construction processes can be evaluated to reduce the emission of harmful substances. To demonstrate this process, quantitative indicators can be developed through indoor and outdoor environmental conditions by monitoring them with an embedded sensing technology (i.e., Internet of Things, IoT) from the unit building to the urban scale.

- Quantification of human health and development of a health-combined index: The combined index described in the previous section can reduce the emission of hazardous substances in the construction phase as well as in the building operation phase. In particular, it is expected to reduce the respiratory diseases of both the laborers and the building occupants. In the previous studies, experimental research was conducted to estimate the building occupants’ psychological and physiological responses based on their activities and the IEQ condition. To extend this process, psychological and physiological analyses will be conducted for the residents and construction laborers, using a smart sensing technology (i.e., vitro diagnostic device) (Kim et al. 2017a, 2018; Hong, Kim, and Lee 2018).

- Development of a building and construction process management system with a human-environment-building interaction concept: The research methodology called “integrated multi-objective optimization model” can be used to determine optimal strategies for low energy and acceptable IEQ conditions (Kim et al. 2017b). Through the environment combined index and health combined index, a building and construction process management system can be developed for a healthy and sustainable building and city.

Eventually, it is expected that the proposed IPU concept will promote the spread of good health and environment-friendly buildings.

4. Conclusion

The human-indoor environmental quality (IEQ)-building interaction concept can be used by building managers and occupants in enhancing the IEQ and energy performance of buildings in short- and long-term building management. In the future research, the intelligent planning unit (IPU) can assess the psychological and physiological responses and activities of the building occupants more accurately and comprehensively, and is thus expected to be useful for quantifying the IEQ of buildings. It is also expected to contribute to the improvement of the IEQ of buildings in the building industry. Moreover, it can assess the effects of IEQ in terms of the building occupants’ behavior and the
characteristics of buildings, and can thus serve as a guideline for enhancing the IEQ of buildings. Furthermore, it can represent the various IEQ parameters as a simple single index. It is expected to be able to stimulate the building occupants’ and owners’ interest in healthy and environment-friendly buildings, and to enable the decision-makers (the building owners, building occupants, and architects) to accurately and simultaneously estimate the energy savings amount, IEQ improvement, and cost savings amount by building design element, and to understand the value of good health and environment-friendly buildings.

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