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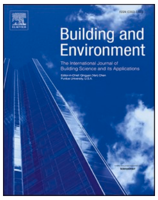

Ten questions concerning occupant health in buildings during normal operations and extreme events including the COVID-19 pandemic

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ABSTRACT

Even before the COVID-19 pandemic, people spent on average around 90% of their time indoors. Now more than ever, with work-from-home orders in place, it is crucial that we radically rethink the design and operation of buildings. Indoor Environmental Quality (IEQ) directly affects the comfort and well-being of occupants. When IEQ is compromised, occupants are at increased risk for many diseases that are exacerbated by both social and economic forces. In the U.S. alone, the annual cost attributed to sick building syndrome in commercial workplaces is estimated to be between $10 billion to $70 billion. It is imperative to understand how parameters that drive IEQ can be designed properly and how buildings can be operated to provide ideal IEQ to safeguard health. While IEQ is a fertile area of scholarship, there is a pressing need for a systematic understanding of how IEQ factors impact occupant health. During extreme events, such as a global pandemic, designers, facility managers, and occupants need pragmatic guidance on reducing health risks in buildings. This paper answers ten questions that explore the effects of buildings on the health of occupants. The study establishes a foundation for future work and provides insights for new research directions and discoveries.

1. Introduction

The topic of occupant health in buildings is an emerging area for both academic research and industry practices. The World Health Organization (WHO) defines health as *"a state of complete physical, mental and social well-being"* [1]. Physical well-being is defined as the appropriate functioning of our bodies and our ability to resist illness. Mental well-being includes more than merely the absence of mental illness; it is comprised of mental resilience, contentment, confidence, and the peace of mind. Finally, social well-being is the ability to build meaningful relationships with others; it is determined by an individual's sense of belonging, and social engagement [2].

The term *"healthy buildings"* is emerging in the literature; researchers have previously focused on *"sick buildings,"* or the "Sick Building Syndrome" (SBS) to address "Building Related Illness" (BRI) [3]. Indeed, the concept of designing buildings to support occupant health has only been recently adopted. A "healthy building" is defined as a built structure that promotes the positive well-being of individuals [4]. Despite the importance of healthy buildings, rather than avoiding sick buildings, we do not have a clear and commonly accepted definition of what "healthy building" means to building professionals and occupants. Moreover, designers do not have a systematic process to incorporate the fundamental definitions of health offered by the WHO, as presented earlier, in buildings.

As the climate, functionality, and technologies drive changes in buildings, there is a need to ensure that buildings can be flexibly adapted to these circumstances without compromising occupant well-being. People spend most of their time (~90%) indoors [5], and buildings are clearly becoming one of the most essential drivers of health. With the outbreak of the SARS-CoV-2 virus, many were required to stay at home, while carrying on with their lives (e.g., studying, working, etc.) in the same built environment over an extended period. It follows that a healthy building should continue to maintain optimal occupant physical, mental, and social well-being conditions during extreme events and over extended periods of time. Therefore, by combining the official definition of health provided by the WHO and taking into consideration

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the aforementioned argument, a healthy building may be better defined as: *a building, including all of its systems, that promotes and sustains the health of its occupants, as a state of complete physical, mental and social well-being.*

As a result of emerging environmental concerns (e.g., climate change, pollution), demographic shifts (e.g., aging population), lifestyle changes (e.g., global epidemics of stress, longer working hours) and the recent COVID-19 pandemic, building professionals and researchers are highlighting the role of healthy buildings in addressing these challenges. This ten questions paper focuses on how health in buildings is conceptualized by building researchers and practitioners. Questions 1 to 4 present an overview of healthy buildings by presenting their effects on health, discussing health assessment metrics and elaborating on the relationship between occupants-centric and performance-based buildings. Questions 5 and 6 focus on the social and economic impacts of unhealthy buildings. Questions 7 and 8 investigate new stressors that affect occupants health in buildings. Finally, questions 9 and 10 examine what emerging technologies can offer as new insights in this field and present opportunities for future research and discovery. Fig. 1 provides a schematic overview of the investigation presented in this paper.

2. Ten questions and answers concerning health of occupants in buildings

2.1. Question 1: How do buildings affect the health of occupants?

"Indoor Environmental Quality (IEQ) refers to the quality of a building's environment in relation to the health and well-being of those who occupy space within it." [6]. IEQ is determined by many factors, including indoor air, thermal comfort, lighting, acoustics, water quality, interior design, spatial organization, and their psychological impacts individually and collectively. The *indoor air* in buildings is a mixture of outdoor air through the mechanical or natural ventilation systems and the recirculated indoor air. The Indoor Air Quality (IAQ) is hence affected by both the contaminants from outdoors and other indoor sources associated with building materials, appliances, excessive moisture, pets, humans, etc. Indoor air contaminants include gas (organic gas such as volatile organic compounds and inorganic gas such as radon and ozone) and particulates (such as mold, asbestos and silica dust) [7]. The health impacts from poor IAQ can be acute, e.g., asthma, throat irritation, shortness of breath, and heart disease [8,9]. Poor IAQ can also cause cancer, chronic lung diseases and bronchitis [10]. In addition to their direct effect on physical health, indoor air contaminants are also associated with elevated negative emotions, amplified aggressive behaviors, degraded attention, and mental fatigue [11]. Building *ventilation* aims to provide and maintain improved IAQ by removing pollutants generated by indoor sources, thus diluting the concentration of indoor contaminants [12]. For instance, Bornehag et al. [13] found a clear dependency between lower ventilation rates and higher probability of respiratory symptoms in single-family houses. In offices, it was found that sick leaves associated with sick building syndromes dropped by 35% when ventilation rates were increased from 12 L/s to 24 L/s [14].

While previous studies heavily focused on thermal comfort, the effect of *thermal environments* on occupant health has been investigated less. Reinikainen and Jaakkola [15] found that SBS symptoms increased when air temperature exceeded 22 °C. The change in temperature from the thermoneutral conditions (22 °C) to mild conditions (16 °C) was associated with the activation of the brown adipose tissue, which maintained the core body temperature through the metabolic process of body heat, and was used for the treatment of obesity [16]. *Daylight* is linked with improved mood, higher sleep quality and lower blood pressure [17]. Sunlight is the natural source for vitamin D, which modulates cell growth and protects the body from diseases like osteoporosis and rickets [18]. Furthermore, *access to natural views* (e.g., green spaces, forests, lakes) has been shown to help office workers overcome job stress and help them shift their mental state from a negative to positive status [19]. The effects of light on human circadian system, which controls the circadian rhythm by regulating the level of melatonin secretion to adjust sleepiness and alertness, have been investigated by building scientists. Circadian lighting systems (i.e., electric lighting system used to mimic sunlight based on color, intensity, angle of projection) deployed in office spaces are associated with enhanced alertness levels, better mood, higher concentration, suppressed depression, and improvements in sleep and agitation [20]. In addition, poor distribution of light sources in an indoor environment can lead to the excessive contrast of vision, known as *glare*. A small amount of glare can be annoying, leading to a loss of attention or concentration [21]. However, exposure to glare for long periods of time can lead to vision problems such as eye strain, impaired vision and even eye injuries [22].

Poor *acoustics*, another IEQ factor, cause occupant dissatisfaction in buildings, especially offices [23], as well as among hospital staff, patients and visitors [24]. Noise in buildings could be generated by outdoor sources, building systems, mechanical and electronic devices (e.g., printers, cleaning equipment, phones) and/or by occupants. In hospitals, background noise can lead to sleep deprivation [25], which can negatively affect the recovery period of patients [26]. In office settings, employees subject to lower noise levels present less cognitive stress and hypertension [27].

Water quality, *distribution,* and *control* in a building as well as *nourishment* are also important factors for occupant health in buildings. Poor design and management of water systems within a building have caused disease outbreaks [28] that in most cases require hospitalization [29]. Such outbreaks can be either chemical or microbial contaminations, and are due to faults in water systems, growth of microbes or

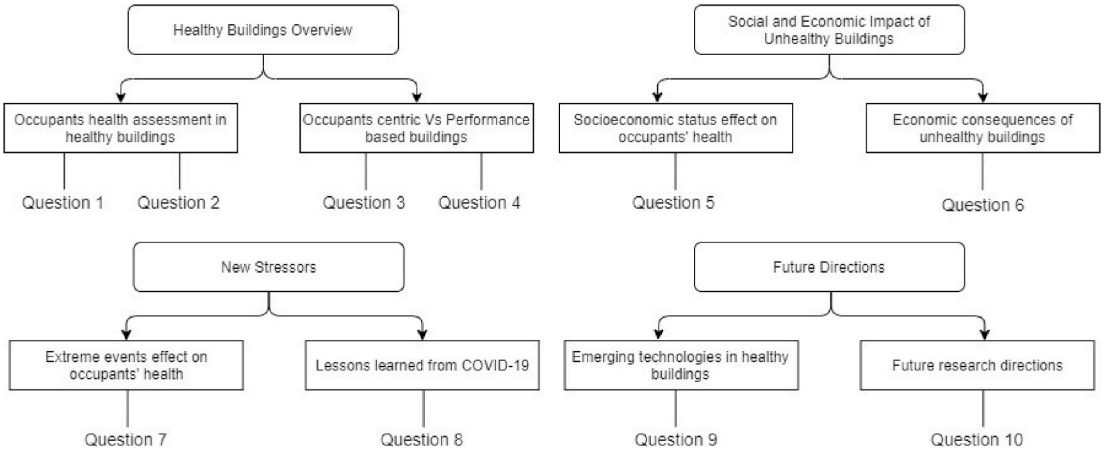

Fig. 1. Schematic overview of the 10 questions.

cross-connection between drinking water and diverse sources of pollution. Microbes in water sources can also be transported via the indoor air. A good example is the Legionnaires disease, which initiates in water sources such as a hot tub, but is spread by aerosolized water droplets via indoor air [30].

Indoor space and *interior design* have a strong impact on occupant health. For example, buildings should provide their occupants with the necessary *physical activity* opportunities since physical inactivity is considered a major cause to premature death and chronic diseases such as type 2 diabetes, cardiovascular diseases and depression [31]. Employers are increasingly providing their employees with active workstations, such as desk treadmills, cycle or sit-stand desks [32] as well as secure bike storage and changing and shower facilities to support active commuters [33]. In addition, building design can allow occupants to have access to dedicated physical activity spaces, such as gyms or provide opportunities for physical activity (e.g., encouraging use of stairs or walking) through active design. Ergonomics minimize strain and stress on the body through well designed environments. Musculoskeletal disorders (MSD), are the injuries and disorders that affect the human's musculoskeletal system, such as muscles, tendons, ligaments, nerves, etc.), and represent a major threat to the health of building occupants due to poor design. Uncomfortable postures can build up high tensions on joints, muscles, and nerves causing the development of serious problems [34]. Research studies over the last two decades show that between 20% and 60% of office workers suffer from MSD related pain [35].

Social health can be influenced through *space organization* by creating areas for individual contemplation and group socialization. For example, comparisons of face-to-face and electronic interactions between office employees, showed that face-to-face interactions were lower in open plan offices in comparison to cubicles [36]. In educational facilities, designers create open spaces to reduce feelings of isolation, and outdoor eating areas to allow for social bonding among students. Nature can be brought into the indoor environment through *biophilic design* with indoor vegetation, fresh air, natural sounds or through natural colors or views of nature. Bringslimark et al. [37] showed that the integration of natural sounds and green plants into hospitals can reduce hospital stays, hasten recovery, and increase pain tolerance. Furthermore, strong correlations have been found between direct exposure to nature within the built environment and reduction of attention deficit hyperactivity disorder symptoms in children [38]. Fig. 2 presents a summary of the healthy building concept and how it affects the physical, mental and social well-being of occupants.

2.2. Question 2: How is occupant health in buildings assessed?

To date, there is no widely accepted occupant health assessment standard. As indicated above, occupant health is the totality of physical, social, and mental well-being, and it is affected by many complicated and coupled factors, which make the assessment challenging. In general, two different methods are widely used to gather data: physical measurements (by using sensors and other instruments) and survey studies. The physical measurements can include those of the built environment, such as temperature, humidity, etc., and those of the occupant, such as heart rate, body temperature.

There are two types of sensors used for occupant health assessments: sensors used to measure the built environment, especially those for IEQ parameters, and sensors used to assess occupants, especially occupant comfort. Sensors that can measure IEQ parameters, such as indoor air temperature, humidity, velocity, radiant temperature, lighting intensity, contaminant levels (including gas and particulate), have been commercially available for many years. Comprehensive IEQ sensing systems that measure multiple IEQ perspectives have also been developed. For example, Choi et al. [39] developed and used a National Environmental Assessment Toolkit (NEAT) cart to measure the IEQ and occupant satisfaction in 20 U S. office buildings over 7 years. Commercial off-the-shelf sensors to measure air temperature, radiant temperature, relative humidity, CO_2, CO, total particulates, volatile organic compounds (VOCs), light levels, and air velocity were built into the NEAT cart, and all data were transferred to a server through a wireless connection.

Another research trend in the recent years is the development and use of biomarkers (physiological measurements) for well-being assessment. For example, skin temperature (e.g., via infrared thermal cameras) [40,41], blood pressure [42], heart rate, perspiration rate [43], galvanic skin conductance [44], and eye movement [45], have all been

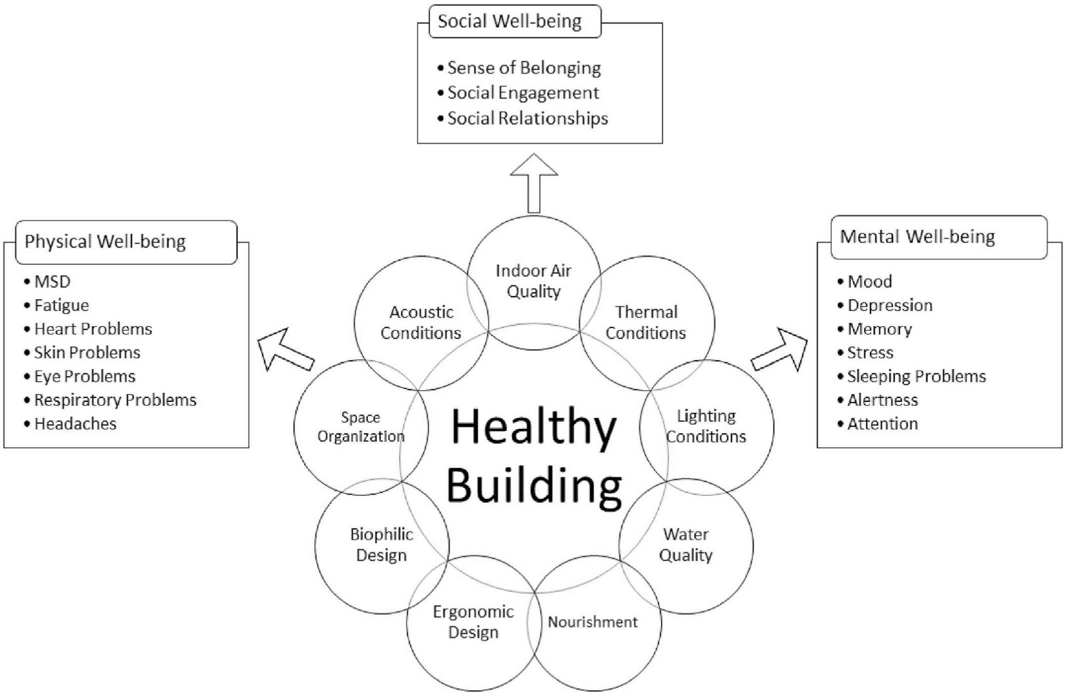

Fig. 2. Healthy buildings concept.

studied for their association with occupants' comfort. Other data have been collected without the requirement to install sensors such as medical tests, sick leave reports, occupant complaints, frequency of doctor visits. Nonetheless, these measures are used less frequently than surveys, biomarkers, and sensors.

Surveys, including both structured and semi-structured surveys (interviews), are also important tools to assess occupant well-being. Post-occupancy surveys have been used for many years by building owners and building researchers and practitioners to understand a building's performance and its impact on occupants. Survey instruments used for IEQ and thermal comfort assessments have been well studied [46]. Surveys that aim at providing a more comprehensive assessment of occupant health have also received some attention in recent years. The BUS (Building Use Studies) Wellness Survey, which combines the pre-existing standard BUS Methodology Occupant Satisfaction Survey and Delos Building Wellness Survey, were developed as a joint effort between ARUP and Delos in 2019 [47]. Many research studies have also developed their own survey instruments to assess occupant health. However, not all published studies make their survey instruments public [48,49]. The effectiveness of survey instrument design in assessing occupant health has generally not been discussed in the literature. In fact, tools to assess IEQ and thermal comfort are better studied than those that assess the integrated physical, mental, and social health of occupants.

2.3. Question 3: To what extent is occupant health considered as an objective?

Recently, building professionals have started to include a more comprehensive view of health into building guidelines. Examples are the Well Building Standard (WELL) from the International Well Building Institute [50], the FitWell from CDC and GSA [51], and the performance-based and sensor-based standard and certification: Reset [52]. WELL [50], the most widespread among these standards, is a performance- and evidence-based system, which evaluates building performance through measuring, certifying, and monitoring features. Specifically, the standard builds upon the following thematic categories: air, water, nourishment, light, movement, thermal comfort, sound, materials, mind, community, and innovation. These categories show that efforts are being made to go beyond traditional thermal comfort and IEQ features, by including non-traditional categories that are related specifically to mental and social health in buildings. A comparison between the Leadership in Energy and Environmental Design (LEED) certification established in 1998 and the WELL certification in 2014 shows that such occupants-centered initiatives are still in nascent. In fact, as of 2020, there are 129,612 LEED-certified buildings [53], compared to 4,917 WELL-certified buildings worldwide [50].

As mentioned in question 1, numerous characteristics and features of a building can impact the physical, mental, and social well-being of occupants. The ways that these building features interact to influence occupant health in different types of buildings vary greatly. Programs like the Living Building Challenge (LBC) also have established metrics to incorporate health in the design process. In the LBC metric, the intent is to encourage designers to design environmental conditions for air quality, visual and thermal comfort to enhance productivity and health. Similar efforts have been directed to building operations evidenced by commissioning services and other facility management tools which aim at improving occupant well-being (e.g. Ref. [54]). Some building codes and standards apply recommendations from ASHRAE, USGBC, or CIBE, which have performance measurement protocols for commercial buildings [55]. Such protocols require comprehensive measurements of IEQ for building performance assessments, which may also be used for occupant health assessments.

Office buildings are typically the focus of occupant health studies for pre-design as well as post-occupancy analyses, followed by educational and residential buildings. It is indeed rare for health to be considered as a design objective among other types of buildings such as retail, industrial buildings, and so on. Additionally, most post-occupancy studies rely on subjective occupant feedback (i.e., surveys, interviews) and longitudinal studies and assessments are limited by the number of occupants and/or number of buildings studied. Currently, due to COVID-19 pandemic, understanding how different features of buildings (e.g., ventilation, humidity, etc.) impact occupant health has become paramount. However, building designers, contractors, operators, and owners may have conflicting information and perspectives that impede the actual implementation of healthy building practices. And, cost is often the sole driver for design, construction and operation practices. The paucity of real-world cases and proof of positive return of investment as well as the lack of well-defined fee structures for the additional scope are some of the obstacles to advancing healthy buildings. While it is clear that more emphasis on designing, constructing and operating buildings with occupant health is needed, such initiatives require constant monitoring and improvement, codification, and advocacy, until it is widely endorsed by building professionals.

2.4. Question 4: What is the relationship between occupant-centric and performance-based metrics?

Buildings account for 33% of the global energy demand [56]. The required energy for buildings is mainly produced by fossil fuels, which result in buildings being responsible for around 19% of the global greenhouse gas emissions [57]. Over the years, ensuring the sustainability of the built environment has focused on 'green' design strategies that conserve natural resources and reduce energy use. Adding healthy building to this vision allows one to bring forth the concept of well-being to the sustainable/green design discourse. Allen and Macomber explain that diverse design strategies could create a nexus of energy and health which will result in tremendous co-benefits [58]. For example, an energy efficient design reduces building energy consumption and as such the greenhouse gas emissions which could be translated into tangible health benefits. Based on the scale of prevented emissions, health professionals could estimate the number of deaths averted, the drop in physical health problems (e.g., respiratory, cardiovascular, etc.) and the reduction in cancer cases.

Furthermore, the literature provides plenty of evidence that supports positive health outcomes of green buildings. Green buildings promote better health conditions in their indoor environments. Occupants report less mental and physical health symptoms in offices, schools and homes designed according to green guidelines [59]. In addition, the green movement is aligned with the energy efficiency concept which circles back to the benefits attained from reduced greenhouse gas emissions [60].

However, these findings are not always consistent [61]. For instance, Thatcher and Milner showed that green office spaces improved perceived occupants' physical well-being but not their mental well-being [62]. Opposite conclusions were reported by Kato et al. [63], where it was found that physical health did not improve in green buildings. Other research studies concluded that green practices can sometimes induce negative health consequences [64]. For instance, it was found that the use of fly ash (waste-based/recycled material) as an additive to construction materials can expose building occupants to toxic heavy metals [65]. Furthermore, an investigation of 37 common products (e.g., cleaning products, air fresheners, etc.) including green and organic ones showed that they emit a range of VOCs into the indoor environment that can degrade occupants health [66].

The above-mentioned examples related to green-healthy building synergies and conflicts point to the fact that occupant health and sustainability can be achieved if buildings are designed and operated with the twin goals of health and sustainability. However, a multi-objective perspective is required. One pathway is by advancing existing building codes, standards, and operation guidelines to include an integrated perspective. With the emergence of healthy buildings, the design choices associated with health such as ventilation and filtering will have significant impacts on the energy consumption, which can be incorporated into updated energy standards. For example, there have been many studies that suggest higher ventilation rate than what is currently proposed would result in better occupant well-being [67].

2.5. Question 5: How does socioeconomic status impact occupant health in buildings?

Low-income and underrepresented minorities are most likely to live in sub-standard houses, which contribute to disparities in health between low- and high-income and minority- and majority-households [68]. Sub-standard building conditions consist of pest infestation, cracks, holes, peeling paint, water leakages, broken ventilation systems [69,70], and are linked with distress, asthma and long-term diseases such as bronchitis and cancer [71,72]. A nation-wide study conducted in Australia, showed that 60% of individuals living in a poor housing quality also draw low household incomes [73]. Similarly, in the U.S., low-income American families assign almost 50% of their income to housing, forcing them to choose between affordability and satisfactory housing conditions [74]. Furthermore, maintaining satisfactory housing conditions requires regular maintenance and upkeep, which most low-income households cannot afford [75]. For instance, a broken ventilation system may cost – relatively – too much to fix, leaving the building either too hot or too cold, and leading to poor indoor air quality. These could have negative health effects, especially for children and the elderly [76,77]. Adamkiewicz et al. [78] showed that low-income families are more susceptible to water leaks in their homes, leading to excess dampness and mold growth, and resulting in increased chances of asthma and respiratory problems. In 2014, following the Flint-Michigan-lead water crisis, blood lead levels were found to be the highest in the poorest neighborhoods [79]. More recently, a study found that the transmission of the SARS-CoV-2 among pregnant women in the city of New York was directly associated with low socioeconomic status of the neighborhood [80].

In the U.S., housing choice is not only affected by the income of a household but is also restricted for minority groups because of racial segregation in residential housing [81]. This segregation is defined as the spatial separation of certain groups based on their ethnicity and race. As such, higher numbers of African American and Hispanic groups live in inadequate housing conditions compared with White counterparts [82,83]. Swope and Hernandez [75] argue that populations that are impacted by residential segregation are more prone to health issues. For instance, asthma cases reported among African American children rose almost 50% between 2001 and 2010 [84], which was associated with poor IEQ in their homes [85]. Other studies showed that the level of indoor air pollutants is higher in African American and Hispanic houses compared with other ethnic groups [86]. In another study, 28% of African Americans rated their homes as “in poor condition.” This rating was correlated with an increased risk of diabetes [87].

Racial segregation and lower housing standards among disadvantaged socioeconomic classes are not only restricted to residential buildings, but have also been well documented for schools and school districts as well [88]. This fact places the health burden on children, one of the most vulnerable populations. Children from low income families in Southern California live in high-traffic areas and attend schools that are exposed to hazardous pollutants [89]. Children studying in schools built in proximity to highways report higher rates of respiratory symptoms, specifically asthma [90]. African American children have the highest rates of asthma cases, while white and Hispanic white children have the lowest rates of asthma. In addition, laborers and employees in blue collar jobs usually work in inadequate working conditions with few amenities, insufficient heat in the winter or cooling the summer, and no control over task lighting [91].

While built environment’s impact on health is well documented, more work is needed to develop a framework of health in the built environment, by integrating the work of social and environmental scientists with those of engineers and building designers. Moreover, disciplines that focus on individual and group health risks in the built environment must partner with engineers, government entities and policymakers to design practices and programs that ensure healthy buildings for both individual and public health. There is a gap in our ability to translate science-based evidence and solutions to reduce health risks in the built environment. And while the issue of environmental justice and its impact on public health is well documented, little has been done to conceptualize *built* environmental justice and health inequalities. It is becoming increasingly apparent that a new or expanded framework of environmental justice that includes indoor environmental quality is crucial, particularly given climate change and demographic stressors as well as global challenges such as the COVID-19 pandemic.

2.6. Question 6: What are the economic impacts of unhealthy buildings?

Driven by financial concerns, building owners tend to focus on the energy aspects of a building for two reasons: (1) energy costs are tangible and returns from an energy investment are easily quantifiable and (2) it is fairly simple to meter the energy consumption in a building [58]. On the other hand, it is not a standard task to monitor occupant health and the practice of quantifying the return on investments in this matter is not common [92]. Overall, economic benefits from healthy buildings can be divided into three main categories: (1) increased rent and resale values, (2) productivity increase, especially in commercial buildings, and (3) reduced indirect costs, such as health savings from reduced sick leaves or energy savings as a result of the more efficient IEQ systems [93].

A growing body of literature shows that improvement of indoor air quality, thermal conditions, lighting, ergonomics and acoustics can boost the productivity of office workers, help them sleep better at night allowing them to perform better the next workday, improve their concentration levels and reduce their fatigue keeping them focused at work [94]. On the other hand, degradation of these conditions leads to quantifiable losses. Mikulic et al. [95] showed that even a slight increase of 2 °C from personal comfortable temperature of an office worker can be the cause of 10% decline of his/her productivity. Another study showed that female office workers performed better at high temperature, while the opposite was true for male workers [96]. These findings also point to individual and group differences and present strong evidence that a “one size fits all” approach in building operations in not comfortable, productive or healthy.

Unhealthy buildings also lead to increased rate of sick leaves (absenteeism) among employees, and reduced productivity while working (presenteeism) due to health conditions, and major financial losses for companies [97,98]. For instance, Mendell et al. [99] estimated that productivity losses from BRI (Building Related Illness) range between $20 billion and $70 billion in the United States only. Nagata et al. [100] conducted a detailed breakdown of the economic burden for different companies in Japan, based on a list of health conditions associated with indoor office environments. Costs were divided into presenteeism, absenteeism and medical/pharmaceutical costs. The results showed that absenteeism costs around $520 per year per employee, presenteeism costs around $3055 and medical costs were $1165. Interestingly, musculoskeletal disorders contributed the most to these economic burdens. In fact, the U.S. Department of Labor estimated that work-related musculoskeletal disorder cases cost around $20 billion in 2013 as direct costs. This value goes up by 500%, considering the indirect societal implications [101].

Healthy buildings are not only important in commercial environments but also key in residential and learning-dedicated buildings. In fact, healthy buildings can increase health care savings and reduce medical costs to companies operating in poor workplaces, to families living in degraded conditions, and to students in substandard learning environments. For example, a meta-analysis study showed that mold and dampness in residential buildings were associated with a 30%–50% increase in reported respiratory problems and asthma cases. If this turns out to be a causal relationship, the total health related costs could be around $3.5 billion [102]. Alsmo and Holmberg [103] found that poor air quality is a major problem that Swedish schools face, and it can degrade the health of teachers and students, while increasing the societal burden through health costs, absenteeism, poor academic performance and productivity losses. In a more recent study, the total health care system costs due to mold and dampness in indoor environments were estimated to be around $1.84 billion and $18.4 billion annually in Canada and the U.S., respectively [104]. Furthermore, Montgomery et al. [105] found that the monetized health benefits from increased filter systems efficiency outweighed the added costs. Federpeil [106] found that 18.4% of complaints collected from 575 buildings in the U.S. were related to IEQ. Healthy buildings can reduce the responses of facility managers to such complaints and as such cut down the related costs.

Recently, the COVID-19 pandemic has showed to us that our buildings are not well equipped to combat airborne transmissions of infectious diseases efficiently. Though no study has linked the effect of inefficient building design on the transmission of virus and as such the consequent economic impact, the threat of the virus on human lives is obvious and its ability to paralyze national economies is evident.

2.7. *Question 7: How do extreme events affect health in buildings?*

Unfortunately, climate change is a major threat for human health both outdoors and in buildings and we cannot consider health in buildings solely from the perspective of normal operations. For example, eight of the ten largest wildfires in California occurred in the last 10 years [107] and these wildfires increasingly happen around more populated areas. As extreme climate events become more severe and frequent, buildings are operated under stress. During extreme heat waves or wildfires, buildings can become threatening to occupant health with high concentrations of air contaminants. A study conducted in six urban areas for one week in Eugene,Oregon, found that indoor gas-phase pollutants were consistently equal to or greater than outdoor concentrations during wildfires [108]. Another study found that warm temperatures and sunlight enhance the production of volatile organic compounds in plants, nitrogen oxides emissions from the soil and other pollutants [109]. Furthermore, since HVAC equipment is sized and selected using normal design day conditions, which is based on a historical climate record, the systems may not have adequate ventilation flexibility or cooling capacity to cope with these events. Moreover, excessive heat waves can cause potential rolling blackouts and wildfires can also result in potential power outages. Inadequate cooling equipment capacity or power outrages during an extreme event in a building can result in a body heat overload, which leads to dizziness, fatigue, fainting and in some cases heat strokes. For instance, Wellenius et al. [110] concluded that the higher the heat index (which is a parameter that combines temperature and humidity), the higher the rate of all-cause emergency department visits and deaths, especially among elderly.

Over-reliance on indoor cooling and ventilation systems during heat waves is an adaptive response by occupants to mitigate rising temperatures. However, this behavior increases electricity consumption and energy demand on the grid and hence greenhouse gas emissions, creating an unsustainable loop. The resilience of buildings to extreme events should be aligned with an urban-scale strategy. It is recommended to set up heat preparedness plans, especially for the vulnerable populations with no access to cooling. Cities should also establish cooling centers, while also advocating for the design of green roofs and cool pavements.

Sandstorms are common meteorological hazards majorly accompanied by fine particles that degrade the air quality, and can result in serious respiratory problems, heart stress and eye infections. Sandstorms mainly occur in deserts and are associated with increased temperatures [111]. Osman and Sevnic [112] predicted that by the year 2070, natural ventilation techniques, in Sudan, will no longer remain beneficial to maintain acceptable thermal environments in buildings given the extreme dry weather conditions. With the intensification of sandstorms, they suggest a shift towards more resilient active cooling strategies like evaporative cooling [113] to maintain comfortable thermal conditions, and the use of ultra-low particulate filters (ULPA) [114] to capture fine sand particles during sandstorms.

Other natural disasters such as hurricanes, tornados and floods, associated with excess moisture, create ideal conditions to the growth of molds in buildings [115]. People with respiratory problems and immune suppression are the most vulnerable in this case. Mold is usually linked to eye and skin irritation, difficulty of breathing and shortness of breath [116]. In 2005, after hurricane Katrina landed in New Orleans, several houses remained flooded for weeks, which caused a heavy growth of mold, bacteria and fungi. Chew et al. [117] found that culturable mold levels were significantly high in these houses, reaching 515,000 colony-forming units/m^3. Similarly, in a survey study addressing the consequences of hurricane Sandy in New York City, Gargano et al. [118] found that 31% of the respondents reported having mold or dampness at their homes.

2.8. *Question 8: What has the COVID-19 pandemic taught us about health in buildings?*

Researchers around the world are still learning about SARS-CoV-2 and COVID-19, including how the virus is transmitted in an indoor environment. We expect a major research and practice shift under the pandemic to focus on Heating, Ventilation, and Air Conditioning (HVAC) design and operations [119], humidity control [120], and spatial configuration and human-building interactions (HBIs).

Traditionally speaking, common ASHRAE Standards, such as ASHRAE Standard-55 [121], Standard-62.1 [122] and Standard-90.1 [123], focus more on the thermal comfort in built environments, ventilation regulations, and energy efficient measures without proactively considering the pandemic. Pre-pandemic, ASHRAE and other organizations investigated and published design guidelines and handbooks for infection control in hospital facilities (e.g., filtration, and negative pressure control by design, etc.) [124]. With special design and code requirements, the infection of typical airborne viruses in hospital facilities should be minimized by default design and operation with the right Personal Protective Equipment (PPE).

ASHRAE issued guidelines on the topic of transmission of SARS-CoV-2 and the operation of HVAC systems [125], along with many other agencies such as the Federation of European of Heating, Ventilation Air-Conditioning Associations (REHVA), the Society of Heating, Air-Conditioning and Sanitary Engineering in Japan (SHASE). However, one *cannot* eliminate the transmission of SARS-CoV-2, even with strict measures in a typical indoor environment. What one can do is to minimize the risk of being infected by the virus through proper measures [126]. A recent review paper [127] compares HVAC related guidelines during the pandemic from various countries and regions, including those issued by ASHRAE, REHVA, SHASE, Architectural Society of China, and the Chinese Institute of Refrigeration. Common countermeasures from all of the above-mentioned guidelines include: a) ventilation with sufficient outdoor air and effective airflow patterns, including proper local nature ventilation; b) air filtration (e.g., using HEPA filters which eliminates over 99.97% of airborne particles down to the size of 0.3 μm), including the usage of portable air cleaners, c) disinfection (e.g., UVGI-ultraviolet germicidal irradiation) [128,129], d) proper operation of HVAC system, such as running system 2 h before and after occupancies; proper maintenance of temperature and humidity; and keep a negative pressure in toilets and check the water seals regularly.

During the COVID-19 pandemic, HVAC operations should not continue as usual. It is not recommended to turn off HVAC systems at any time; even when indoor spaces are not occupied, HVAC operations should be maintained but at lower speed to ensure an effective circulation of air that removes the virus from the building with limited energy penalties. The effect of such strategies on the energy consumption should be further investigated and included in novel energy standards related only to pandemics.

Although most of the terms and suggestions from the reviewed guidelines are similar, the exact ventilation rate that would minimize the transmission of an airborne virus, such as SARS-CoV-2, is not provided, and needs further research. The well-known Wells-Riley model [130] links the infection risk in a given room to the number of infected persons, the quanta produced by one infector, the duration of exposure, and the local ventilation rate, which illustrates that the ventilation rate can play a critical role for reducing the infection risk. In the 2020 ASHRAE virtual conference, Yuguo Li [131] pointed out that better ventilation and staying away from crowded and poorly ventilated areas may help reduce infection risk. His preliminary study showed that 8–10 L/s per person ventilation will result in sufficient ventilation to minimize the COVID-19 transmission. However, whether we can apply the Well-Riley model and, if we can, how to apply this probabilistic model to estimate the infection risk during COVID—19 are still debatable even though this model has been used by some researchers [132] and practitioners [133] for COVID-19 studies. Furthermore, currently, the quanta correlation for SARS-CoV-2 is not determined, which needs more bio-experiments with the virus. Other alternative approaches could include the dose-response approach [134] and the G-N model [135].

A preprint by researchers at the University of Oregon has reported sampling in hospital air-handling units and has found viral RNA more or less throughout but there was no outbreak [136]. This is not surprising to most who understand aerosol dynamics and filtration. While more research is needed on this topic, this observation lends support to the hypothesis that the circulating strains of SARS-CoV-2 might not be sufficiently virulent and that the concentrations found in well-ventilated spaces may not pose a significant infection risk. However, when ventilation is poor, the situation is different. It is possible that continuing mutations will eventually produce a SARS-CoV-2 that is more infectious by the airborne route, which would necessitate a change in the approach for effective engineering controls. In a recently published rapid review paper [137], the authors identified fourteen studies that attempted to examine whether HAVC system played a role in the spread of SARS/MERS/COVID-19. Based on this paper, there are evidences that HVAC system has aided the spread of SARS-CoV-1 and MERS-CoV. Yet the limited cases (six) that examined SARS-CoV-2 have drawn conflicting conclusions. More studies are certainly needed to better understand how SARS-CoV-2 transmits in a building and HVAC systems.

Low Relative Humidity (RH) (e.g., less than 40%) is associated with the higher survival and increased infectivity of RNA of influenza and other viruses [138]. Thus, humidity is an indoor environmental factor that affects the survival of SARS-CoV-2 through three aspects: (1) at low RH levels, droplets become droplet nuclei, remain in the air for prolonged periods of time and travel for long distances, (2) viruses and bacteria thrive on dry conditions, and (3) the human mucus barrier weakens with low humidity levels [127]. ASHRAE has recommended that the RH should be maintained between 40% and 60% within the built environment [139], which can help reduce the COVID-19 infection risk, while minimizing the risk of mold growth and keeping a comfort range for occupants. Similarly, the SHASE has recommended to set the temperature in indoor environments between 17 °C and 28 °C and keeping the indoor humidity levels between 40% and 70% [127].

In addition to HVAC design and operations, buildings can also increase the spread of COVID-19 due to spatial configuration and human-building interactions (HBIs) that take place in a building. From a social health perspective, designers encourage social interactions through their design decisions. Moreover, occupant density in a building is guided by building programs and the activities that take place in a building (e.g., some building types like schools and offices have high-occupant density). Higher occupant density results in higher indoor activity but also increases the probability of interacting with an infected occupant, hence increasing the chance for virus transmission. Current buildings are not designed to accommodate 6–10 feet separation between occupants (i.e., social distancing), and corridors, elevators, and stairwells do not provide adequate space for social distancing, nor do open office space arrangements with dense cubicles. Occupants directly and indirectly interact with their buildings (e.g., touching surfaces for opening doors, calling elevators, adjusting temperature). Virus particles can be deposited directly or resuspended on these surfaces due to mechanical system operations, or natural occupant actions such as walking or talking. The virus can also survive on a surface from a couple hours to 5 days depending on the surface material, exposing occupants to the virus [140]. However, while there is evidence that SARS-CoV-2 is transmitted through droplets, more research is needed to understand transmission of the virus via surfaces and what kind of prevention measures should be taken from building design and operation perspectives and how long these measures should be implemented. Understanding the relationship between spatial configuration and viruses transmission can ensure better decision making when we design future office spaces, to be prepared for the next pandemic [141].

2.9. Question 9: How can emerging technologies help achieving healthy buildings?

Emerging technologies have allowed occupants to interact with their buildings in novel and smart ways. New technologies related to the building envelope, thermal energy storage, and sensors not only help achieve energy efficiency but also improve IEQ and provide healthy environments [142]. Studies show that light quality impacts sleep patterns and health [143]. Novel solutions on lighting sensors, and control (including occupant sensors and light sensors), and lighting devices (e.g., LED, circadian lighting) can ensure that light levels are adjusted to user requirements. During the COVID-19 pandemic, emerging technologies have increasingly been used to prevent the spread of the virus. For example, using occupant movement sensor information to manage office space, using air quality sensors with occupancy information to refine ventilation strategies and to prioritize areas for cleaning [144]. In general, sensing technology associated with healthy buildings can be classified to two different approaches: non-wearable sensors (NWS) and wearable sensors (WS) [145]. NWS systems require the sensor to be located in the indoor environment to capture occupant data. Example of NWS systems include laser range scanners, infrared sensors, time-of-flight cameras, and floor sensor mats, just to name a few. WS systems are to monitor the occupant on the individual bases with the use of sensors located on several parts of the body, such as feet, knees, thighs or waists. These WS systems include accelerometers, gyroscopic sensors, magnetometers, force sensors, extensometers, goniometers, active markers, electromyography etc. There are challenges related to each type of system. Specifically, NWS may be expensive and require compliance due to privacy issues [146] while WS can be intrusive and may not been wore at all times, and if so, would be ineffective [147]. Lately, technology advancements in sensing explore a hybrid approach to take advantage of joint power of NWS and WS. We would expect such system to play more significant roles in the arena of healthy buildings.

To translate these new capabilities from emerging technologies into practice, Artificial Intelligence (AI) may lead the way. Using occupant sensors as an example, there is growing interest in developing AI solutions on multi-scale, multi-modal data such as feature engineering and predictive modeling on multi-modal, multiscale data [148] for health monitoring [149,150]. By linking health with buildings, AI-based learning and controls such as Adaptive Neuro-Fuzzy Inference System-based (ANFIS), and Artificial Neural Network-based (ANN) control [151] are employed to assess IEQ. Another important application of AI is proactively monitoring building operations (e.g., fault detection, diagnosis and prognosis) to ensure healthy environments are provided for occupants. Kim et al. [152] and Rogers et al. [153] present a comprehensive review of these efforts. Among all these efforts, we should be aware that the performance of the AI models (e.g., machine learning, deep learning) is contingent upon the availability of large-scale datasets. In developing the models, it is critical that purely data-driven (model free) approach should incorporate domain knowledge to obtain a much-needed performance gain. For example, models employing domain adaptation or transfer learning may be designed to leverage existing large datasets in other domains. New models amendable to explicit incorporation of domain knowledge might be the direction to be pursued.

In summary, emerging technologies empowered by AI enable real-time sensing, learning, decision making and prediction showing significant potential for realizing healthy buildings. These advancements will transform almost all aspects related to healthy buildings ranging from occupant health monitoring, human-building interactions, building fault detection, diagnosis and prognosis, to advanced building controls.

2.10. Question 10: What are the future research directions for healthy buildings?

Despite the efforts outlined in this paper, the building community needs to establish common standards and guidelines for evaluating how buildings should be designed, constructed, and operated for promoting occupant health. More research is needed to understand the strengths and weaknesses of the new standards and guidelines. Furthermore, how to apply the guidelines for buildings in extreme events, such as an infectious disease pandemic, is not clearly defined. Clearly, emergency preparedness guidelines need to be developed to address these deficiencies.

However, in order to achieve the goal of healthy buildings, ***first*** we need a more in-depth understanding of how to link building- and occupant-related parameters to assess physical, mental and social health. Moreover, we need to investigate how each sub-category of physical, mental, and social well-being in buildings contributes to the overall impacts of buildings on health. Most of the existing work in this area either use self-reporting mechanisms, or they are limited in terms of their generalizability (limited number of occupants and/or number of buildings studied), and duration (lacking longitudinal studies). Also, the effectiveness of survey instrument design for assessing occupant health is nascent at best. How to integrate the physical measurements and surveys to provide an effective assessment of an occupant's physical, social, and mental health is an open question that needs to be tackled first. There is a need to conduct large-scale field studies on the health protocols and standards worldwide, like the ASHRAE global thermal comfort database. However, even within the building science community, researchers with expertise in IEQ, experts in lighting and noise, and those who study thermal comfort are siloed and the integrated impacts of lighting, air, noise, and temperature on different building types among diverse occupants are still not well understood. To achieve healthy buildings, we *must have* a holistic, interdisciplinary research framework through which experts in building science, health, data science, and artificial intelligence collaborate in a coordinated effort.

The average age of commercial buildings is 50 years and average lifespan of any large-scale structure is about 75–100 years. This means that buildings will likely outlive their occupants. Thus, assessment of buildings in terms of healthy or unhealthy must be part of a *continuous monitoring* effort rather than a one-time assessment. Sensor costs, including wiring and configuration, have been a market barrier for real-time IEQ measurements. Sensors that measure contaminants are typically more expensive and less robust than those that measure thermal, lighting, and noise. To scale and adopt health assessments, we need sensors that are less expensive, less intrusive, and more affordable. Indeed, while we are adapting to and adopting technology in all aspects of our lives, buildings are no exception. We envision a future of buildings equipped with intelligent furniture embedded with IoT devices that adjust to our preferences, apps that track energy, light, and audio systems being operated based on health preferences, computer vision solutions to track our movements in buildings, metro stations, and public spaces. These advancements can help us remain healthy and safe, for example, by providing safe passage or alarms during a building emergency. However, the research community must address the issue of privacy risks and security breaches that may result from collecting and sharing information about building occupants, their activities, habits and their health. Additionally, there is a non-trivial capital cost associated with introducing these technologies in healthy buildings; this must be weighed against the social and economic costs of unhealthy buildings. As with any adaptation gap, the main barriers are measurements for the return of investment for healthy buildings and tangible examples of practical investments with high returns. As Allen and Macomber suggest [58], one way to address these barriers is to quantify healthy performance in buildings (i.e., Health Performance Indicators, HPI).

Research on Human-Building Interaction (HBI) focuses on improving the interface between humans and buildings by studying building occupants and understanding why and how building users interact with their environments. This information is then used to develop novel technologies, interfaces, tools to improve human experience and to achieve shared human-building objectives, such as energy efficiency, safety, and health. As a result of the COVID-19 pandemic, new HBI strategies, such as voice activated elevators, doors, and water fountains, hands-free light switches and thermostats, surfaces with antibacterial fabrics and finishes will find their way into building design. Buildings will be designed or retrofitted to operate in a more adaptable way, for example, movable walls and partitions to reconfigure spatial arrangements for reducing the probability of infectious diseases or redesigning spaces to ensure physical distancing and restricting movement in congested areas.

Most of the global workforce was forced to work from home at some point during the 2020 pandemic. A new building type that accommodates hybrid working/living and promotes health, while ensuring productive and work-life balance might emerge. Further, the more we understand the impact of buildings on health, the more likely we will be to extend the research efforts to include construction materials and building maintenance. For example, some of the emerging research topics include designing natural ventilation systems to reduce mechanical air conditioning, studying the effect of airflow, light, humidity and surface materials in virus transmission, and developing building materials that facilitate filtration, and sanitation. Finally, evidence-based research that quantifies the impact of new strategies, solutions, and technologies on the economy (flexible leases, co-working spaces, reduced commuting due to remote work), social goals (happiness, connectedness) and environmental goals (energy efficiency, pollution) is needed.

3. Conclusion

The impact of buildings on occupant health has been highlighted and discussed in this paper. It is a topic that has recently gained increased attention not only from the building community, but also the general population in the light of the COVID-19 pandemic. It is now more widely accepted that buildings are central to controlling the spread of infectious diseases. There is a crucial need to improve our understanding of the effects of buildings on occupant health as well as the factors that promote occupant health in buildings. Given that we spend most of our time within our homes, schools, offices, and other indoor spaces, it is imperative to understand the health consequences of building design, construction, use, operation and maintenance. As outlined in this paper, there are several challenges – and research opportunities – that must be addressed by the building community to better understand the health implications of buildings on occupants. An interdisciplinary approach that brings together building scientists, architects, health professionals, data scientists and engineers, coupled with long-term and multi-scale assessments, interventions and controlled experiments to better understand health implications of buildings is needed. Likewise, more work is needed to establish common standards and frameworks, focusing on occupants rather than the building itself, to evaluate how buildings can be designed to support health and happiness.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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