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Creating a comprehensive framework for design, construction and management of healthy buildings

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ABSTRACT

While healthy buildings are investigated in academic research, practice, and policy, they often fail to address the needs and gaps due to insufficient knowledge transfer between them. Moreover, there is no general definition of healthy buildings that could act as a reference for different stakeholders of the building sector. Therefore, this paper presents a novel framework for healthy buildings and a definition for compiling existing knowledge and addressing the needs and gaps. The holistic approach of the framework was developed through an extensive literature review and tested with 12 building case studies in the major European climate zones. The framework outlines five different dimensions (improving mental and physical health, designed for human needs, sustainably built and managed, resilient and adaptive, empowering people), including 24 indicators and sub-indicators. The validation of the framework revealed that it is possible to assess different building projects against different indicators under each dimension. However, challenges remain due to issues such as lack of time, cost of data collection, or lack of documentation. The developed framework provides a balanced approach that promotes both individual well-being and broader sustainability goals. It provides necessary guidance to inform practitioners and policy makers as well as other building sector stakeholders to integrate healthy buildings thinking into their project development, assessment, and decision making.

Abbreviations:			
BPIE	Buildings Performance Institute Europe	HVAC	Heating, Ventilation, and Air Conditioning
BSO	Building Stock Observatory	IEA	International Energy Agency
CO	Carbon Monoxide	IAQ	Indoor Air Quality
CO_2	Carbon Dioxide	IEQ	Indoor Environmental Quality
COPD	Chronic Obstructive Pulmonary Disease	ISO	International Organization for Standardization
DMC	Damp/Mold/Condensation	JRC	Joint Research Center
EC	European Commission	MBx	Multiple Benefits Tool
EPBD	Energy Performance of Buildings Directive	NBS	Nature-Based Solutions
EEA	European Environment Agency	NGO	Non-Governmental Organization
EURATOM	European Atomic Energy Community	PM10	Particulate Matter with a diameter of 10 micrometers
EUROSTAT	Statistical Office of the European Union	PM2.5	Particulate Matter with a diameter of 2.5 micrometers
EU	European Union	ROI	Return on Investment
EU-27	European Union (27 member states)	SBS	Sick Building Syndrome
WHO	World Health Organization	SVOCs	Semi-Volatile Organic Compounds
WGBC	World Green Building Council	VOCs	Volatile Organic Compounds
WMO	World Meteorological Organization	WEI+	Water Exploitation Index Plus
EMFR	Electromagnetic Field Radiation	WELL	WELL Building Standard

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1. Introduction

1.1. Background

The building sector has been receiving a lot of attention from policymakers and the research community, particularly regarding the whole building life cycle embodied and operational energy use and greenhouse gas emissions. Buildings in the European Union (EU) contribute to 35 % of the EU's energy-related greenhouse gas emissions [1] and 43 % of final energy consumption [2]. The building sector is one of the largest industries in terms of natural resource consumption [3,4]. How buildings can use less energy and resources has been the focus of EU policies for some time, with the most prominent steps taken towards the recast of the Energy Performance of Buildings Directive (EPBD) [5]. Construction processes can have negative consequences on the environment [6] through resource depletion [7], fossil fuel extraction, poor outdoor environmental quality, and high energy-intensive processes such as steel and concrete production [8]. Construction processes can also negatively affect the environment through local environmental destruction [9], leaching of chemicals into waterways [10], and the emission of greenhouse gases both during the production and operation of a building [11,12]. Thus, construction affects some of the planetary boundaries [13], as well as planetary health overall [14]. Moreover, building construction impacts the aspects of societal cohesion, occupant interaction, and inclusivity, as well as human health and comfort in case of poor indoor environments, and human adaptability and response to climate change. The research community, industry actors, and recently, some EU policies highlight that buildings can significantly affect human health and well-being if not considered in parallel to decision-making for energy efficiency and reduction of carbon emissions during their life cycle. The main research publications, industry reports, and policies are outlined in the next three subsections.

1.1.1. Academic approach to healthy buildings

Academic research approaches healthy buildings from a variety of angles. A large focus lies on the influences of buildings on people's physical and mental health (short: health). This relates to research on toxic substances in building materials [15], building design [16–18], including bioclimatic design [19], adapting buildings to people's needs [20], green or sustainable retrofitting [21,22] and the effects of poor housing or construction [23–25]. Also included is research on indoor environmental quality (IEQ) – including indoor air quality, ventilation, thermal conditions, light, noise, dampness, and mold [26–36]. More social aspects, such as affordability and energy poverty [37–42], community and neighborhood cohesion, and social isolation [43–47], are investigated. Greener neighborhoods [43] and environmental aspects such as the effects of nature on people's health [48–52], or the effects of climatic influences, such as hot weather on overheating [53], or extreme weather events and how buildings can adapt to these changes [54–58], or a combination of the above [59,60] is another focus area. Each of these research directions investigates the negative and positive effects of these influences on human health and considers different age groups and occupants, such as children, elderly, or disabled. Some researchers have also investigated the health of buildings, from structural safety and maintenance issues [23,24] or longevity and sustainability of construction materials [61].

Another area of research in academia is how people can improve their health in buildings, which is often associated with the positive effects that it has on public health [62,63]. Health and buildings are also investigated independently of each other, primarily due to the complexity of the two domains. For example, the vast literature on behaviors impacting and improving health is often dissociated from buildings. Research on renovation and energy efficiency [64–66] is at times conducted independently of their health effects, which highlights the disassociation between buildings and health. However, since renovation and energy efficiency projects on buildings can also have negative effects due to lack of adequate ventilation [67,68], a health focus is required to be studied in depth. Likewise, research looking into the effects of changing climatic conditions on buildings is conducted independently of considering direct health effects [58,69,70], which are becoming more prominent with time, such as overheating.

Based on the studied literature, existing research can be categorized into three overarching domains: (i) Health, (ii) Buildings, and (iii) Climate. Most of the existing literature focuses on a combination of at least two of these domains, with a smaller number considering all three. Disciplines, such as engineering or public health, tend to focus on one or a combination of two aspects, while fewer examples exist where multidisciplinary research teams investigate all three aspects. Social scientists tend to have a broader scope in their work, yet this could come at the detriment of leaving out important physical building aspects.

1.1.2. Building sector approach to healthy buildings

For industries and organizations (e.g., trading bodies, NGOs) working in the building sector, there is increasing awareness of incorporating all three domains (health, buildings, and climate) into the concept of healthy buildings. The UK Green Building Council published a report on health and well-being in homes in 2016 [71], integrating both homes and neighborhoods into their models. The World Green Building Council (WGBC) published a health and well-being framework with six principles for a healthy, sustainable built environment in 2021 [72]. The Irish Green Building Council published the Healthy Homes Ireland report in 2023 and incorporated a variety of different aspects affecting the health of residents [73]. VELUX has published the Healthy Homes Barometers since 2015, increasing the focus on multiple elements affecting health with each iteration, as well as the Compass Model, which considers health aspects [74].

There is also a prominent focus on how healthy buildings can be of benefit to businesses and companies. Increasing the productivity and performance of employees has been a major focus of the Healthy Buildings Program at Harvard University [75]. Certifications, such as the WELL building standard [76], incorporate productivity into their certification system of commercial and office buildings. The WGBC framework considers productivity in the workplace as a core driver for the business sector in driving healthy buildings [72]. Moreover, increasing the value of buildings by monetizing their benefits in terms of health and well-being is another focus area. The recent EU-funded syn.ikia project, which looks at sustainable plus neighborhoods, developed a multiple benefits tool (MBx tool), incorporating both health, economic and environmental aspects through social cost-benefit analysis to determine the value of a building beyond its construction costs through higher return-on-investments (ROI) [77]. The Joint Research Center (JRC) also published a report highlighting how renovations can increase the value of buildings, mentioning that financial stability can reduce health-related costs due to healthier buildings [78]. McKinsey published a report highlighting that focusing on health aspects can optimize benefits for real estate stakeholders [79].

1.1.3. Policy approach to healthy buildings

In policy, healthy buildings are starting to receive a more integrated focus. In 2015, the International Energy Agency (IEA) published the first report on the multiple benefits of energy efficiency, including health as a benefit [80], which highlighted the sectoral gaps and necessary actions. The JRC also published two reports, asking Member States of the EU to consider the health effects when implementing the previous version of the EPBD and on untapped multiple benefits through environmental and building policies [81,82]. The recast of the EPBD includes a few elements associated with health, such as IEQ, community, and affordability [5]. This inclusion is a big step, as health has previously not been a consideration in building policies at the EU level. However, health is a competency of each Member State and is governed by regional legislations that are often not comprehensive to enforce best practices. Policy on healthy buildings would need to be enacted by each Member State independently after the new EPBD is enforced in 2026 for example, regulations on ventilation or daylighting.

The EU created an EU Health Policy Platform, which aims to be “the main forum for communication and cooperation between health interest groups and organizations, and the European Commission” [83]. However, this platform focuses on public health and food and, as of yet, does not consider health in buildings.

1.2. Knowledge gap

The research community has produced a vast knowledge base on a variety of aspects affecting health in and of buildings, giving a good overview of the relationship between health and buildings. The quantitative review by Ige et al. [60] on studies that investigate the relation between various building design aspects and health is one of the first reviews starting to integrate this vast knowledge base. Some gaps in existing research were identified by Liu et al. [84] on healthy buildings review, such as the need to develop a coherent approach to respond to the predicted increased focus on healthy buildings in the construction industry, which narrowly defines green buildings as healthy buildings.

On an individual level, most of the research has been carried out by investigating the effects of buildings on mental and physical health [33,36,42,85]. The energy efficiency of buildings also receives much research attention, yet often without considering health aspects [64,65]. Similarly, research on life cycle emissions from buildings [11] tends to disregard health aspects, and there are no impact categories considered to evaluate direct health impacts over the life cycle of buildings. Existing research on the adaptability and resilience of buildings in different climate zones [58,86,87] can be extended to include human adaptability and resilience to changing climates. Behavioral health aspects are often investigated by looking at the public health benefits [46] and could be enriched by expanding this research area to behaviors inside a building.

The healthy buildings research area could also benefit from adding research on knowledge and skills on both health and buildings aspects, which so far is missing. This addition would be useful in terms of how occupants or users can act to keep themselves healthy by understanding how a building works. Relatedly, increasing the knowledge and skills of people working in the building sector on factors that influence the health of people and buildings would be a beneficial addition. An area to include in healthy buildings research is how to design buildings to fit human needs. As Table 1 lists key review articles, very limited research was carried out looking at the health aspects of building design. More specifically, existing design knowledge can be helpful in further broadening the scope and including design as an integral aspect of healthy buildings.

What is missing is, therefore, two-fold: (1) compiling the existing research on healthy buildings by integrating results and lessons from the various disciplines and practices, and (2) integrating all these aspects into a coherent and holistic framework. While inter- and multi-disciplinary initiatives exist, they have not yet been assimilated into building projects that integrate different knowledge directions around health. Many existing frameworks or models developed by non-academic organizations add significant value to a holistic understanding of healthy buildings, yet they tend to focus on specific building types, such as homes, offices, or built environments like neighborhoods [71,72]. There also does not yet exist a definition of healthy buildings that includes the holistic, multi-dimensionality of the concept [84] and which different stakeholders across academia, industry, and policy agree on. The World Health Organization’s definition only touches upon healthy housing, leaving out other types of buildings [90].

Table 1 provides an overview of academic review articles, major reports from the building industry, as well as the EPBD legislation from policy. Publications were chosen based on their coverage in the three identified domains of climate, health, and buildings.

1.3. Paper objective

This paper contributes to the healthy building community by creating a holistic, coherent framework that synthesizes academic contributions across various disciplines alongside insights from the building and public sectors. The paper further provides a novel definition of healthy buildings, which incorporates the individual aspects into a combined understanding relevant to most stakeholders. By focusing on all building types, this paper creates a framework that academics and researchers, the built environment professionals, the health sector, and the public sector can use for their specific needs and relate to in their day-to-day lives. Rather than merely reviewing existing literature, this paper uses the literature review as a foundation to support the creation of this new framework. The framework is further validated through application in real-world case studies, which demonstrate its practical relevance and adaptability. Additionally, the paper supports the framework with detailed indicators and sub-indicators, systematically linking them to existing datasets across different countries and climates, ensuring its applicability in various geographical and environmental contexts.

The paper is structured as follows: section 2 introduces the methodology used, outlining the key steps undertaken in the research and validation processes. Section 3 presents the results of the study, beginning with the introduction of a comprehensive definition and the five dimensions of healthy buildings in section 3.1. This is followed by the detailed linkage of indicators and sub-indicators for each dimension with the available data in section 3.2, while Section 3.3 demonstrates the validation of the framework through various case studies. Section 4 delves into a discussion of the key findings, highlighting the strengths and limitations of the study and suggesting directions for future research. Finally, section 5 concludes the paper, summarizing the main contributions of the research.

2. Methodology

The development of the framework for healthy buildings was carried out in two major phases, including in total five steps (see Fig. 1).

2.1. Literature review and framework conception

The first phase consisted of two steps:

- **Step 1:** An extensive gap analysis was conducted through a literature review using the academic (e.g., journal papers, reports, books) and industry literature (e.g., market reports, case studies, etc.) on the topic of healthy buildings to establish an understanding how healthy buildings are understood and perceived in the building sector in the current situation. This topic was especially studied in the context of existing policies, regulations, and certification systems in the EU, such as the EPBD [5], Fitfor55 [91], Level(s) framework [92], and green building certifications. Gaps were identified based on the knowledge of stakeholders, existing policies, communication, and building and construction practices.
- **Step 2:** Focusing on the knowledge and gaps identified in step 1, five major dimensions were identified under which the framework could be defined and designed: D1: improving mental and physical health,

Table 1
List of recent publications from academia, building industry, and policy (not a comprehensive list).

Authors	Field (academia, industry, NGO)	Year	Type of publication	Specific focus area	Domain
Liu et al. [84]	Academia	2023	Review Journal Article	Review of healthy buildings research	Health + Buildings + Climate
Ige et al. [60]	Academia	2019	Review Journal Article	Review of healthy buildings research	Health + Buildings + Climate
Schweiker et al. [33]	Academia	2018	Review Journal Article	Diversity in thermal human perception	Health + Buildings
Wang et al. [85]	Academia	2018	Review Journal Article	Individual differences in thermal comfort	Health + Buildings
Maqbool et al. [42]	Academia	2015	Review Journal Article	Affordable housing impact on health	Health + Buildings
Boyce et al. [36]	Academia	2010	Review Journal Article	Light and its effect on health	Health + Buildings
Higuera-Trujillo et al. [88]	Academia	2021	Review Journal Article	Cognitive-emotional design of architectural space	Health + Buildings + Climate
Hafez et al. [64]	Academia	2023	Review Journal Article	Energy efficiency in sustainable buildings	Buildings + Climate
Chen et al. [65]	Academia	2020	Review Journal Article	Internal and external factors influencing energy-efficient design of buildings	Buildings + Climate
Buyle et al. [11]	Academia	2013	Review Journal Article	Life cycle assessment in the construction sector	Buildings + Climate
Elnagar et al. [86]	Academia	2023	Review Journal Article	Qualitative assessment of integrated active cooling system	Buildings + Climate
Felicioni et al. [87]	Academia	2023	Review Journal Article	Sustainability and resilience in the building sector	Buildings + Climate
Walsh et al. [58]	Academia	2017	Review Journal Articles	Climatic zoning for the built environment	Buildings + Climate
Antwi-Afari et al. [89]	Academia	2021	Review Journal Article	Sociometric analysis of circularity in the construction industry	Buildings + Climate
World Green Building Council [72]	Building industry	2023	Report	Health and wellbeing framework for the built environment	Health + Buildings + Climate
UK Green Building Council [71]	Building industry	2016	Report	Health and wellbeing in homes	Health + Buildings + Climate
International Energy Agency [80]	Building industry	2015	Report	Multiple benefits of energy efficiency	Health + Buildings + Climate
VELUX [74]	Building industry	2024	Report	Compass model for sustainable buildings	Health + Buildings + Climate
EU [5]	Policy	2024	Legislation	Energy Performance of Buildings Directive	Health + Buildings + Climate
EU [83]	Policy	2024	Website	Health Policy Platform	Health

D2: designed for human needs, D3: sustainably built and managed, D4: resilient and adaptive, D5: empowering people. These dimensions represent thematic areas that are critical to addressing different aspects of healthy buildings and their definition. Furthermore, each dimension included the identification of several indicators that could be monitored to establish the status quo of any building and evaluate its health.

2.2. Identification of case studies and framework validation

The second phase had the following three steps:

- **Step 3**: Relevant case studies were identified from different climatic zones of Europe to test the applicability of the framework (dimensions and indicators). The selection was made based on past projects, including building uses (public, commercial, residential), renovation projects, new build projects, and climatic zones across the EU. 12 selected case studies are based in Belgium, Denmark, France, Germany, the Netherlands, Slovakia, Spain, and Sweden. These case studies demonstrate good practices focusing on specific strengths of healthy buildings, such as using natural construction materials, enhancing indoor air quality, using both active and passive cooling systems, and integrating nature into the built environment.
- **Step 4**: The 12 case studies were mapped against each indicator in the validation process using both qualitative and quantitative data. For example, if a case study had installed a pond or built a green wall, this was mapped to the indicator 'blue and green infrastructure.' Finally, a consolidated scoring was created for each of the five dimensions. Indicators and sub-indicators were grouped to form fewer indicators per dimension. This step was conducted to group indicators that touch upon related concepts so that policy gaps and recommendations could be formulated. From the simplified list of indicators, a score was created for each of the case studies. If a case study incorporated measures relating to the indicator, a score of 1 was given. If no measures were taken, a score of 0 was given. A sum of scores based on equal weighing for each dimension was created for each case study and for all case studies together. Since each dimension has a different number of indicators, each dimension was normalized to a score of 10 for comparability. That means the highest score per dimension is 10, and the lowest score is 0. Furthermore, following the case study validation, quantitative national data for each indicator was also used to validate the five dimensions of the framework and how feasible it is to track the state of healthy buildings with them. For the selected indicators, different datasets (e.g., EUROSTAT [93], ODYSSEE-MURE [94], Building Stock Observatory (BSO) [95]) were investigated to obtain national data that could show an empirical trend in the state of healthy buildings in respective case study countries as well as emerging trends in the countries and for the EU.
- **Step 5**: The list of final indicators was adjusted based on the testing results from the 12 case studies, and the framework was finalized in this step with the identification of datasets that are available at the EU-27 level to track the progress of healthy buildings. The finalized framework was used to develop a set of recommendations to make healthy buildings the center of attention and integrate dimensions of health, sustainability, and resilience in mainstream building and construction practices.

3. Results

3.1. Definition and dimensions of healthy buildings

Healthy buildings are crucial components of our built environment, fundamentally prioritizing the health and well-being of those who inhabit them. This paper introduces a new definition of healthy buildings as follows: "Healthy buildings emphasize the health and well-being

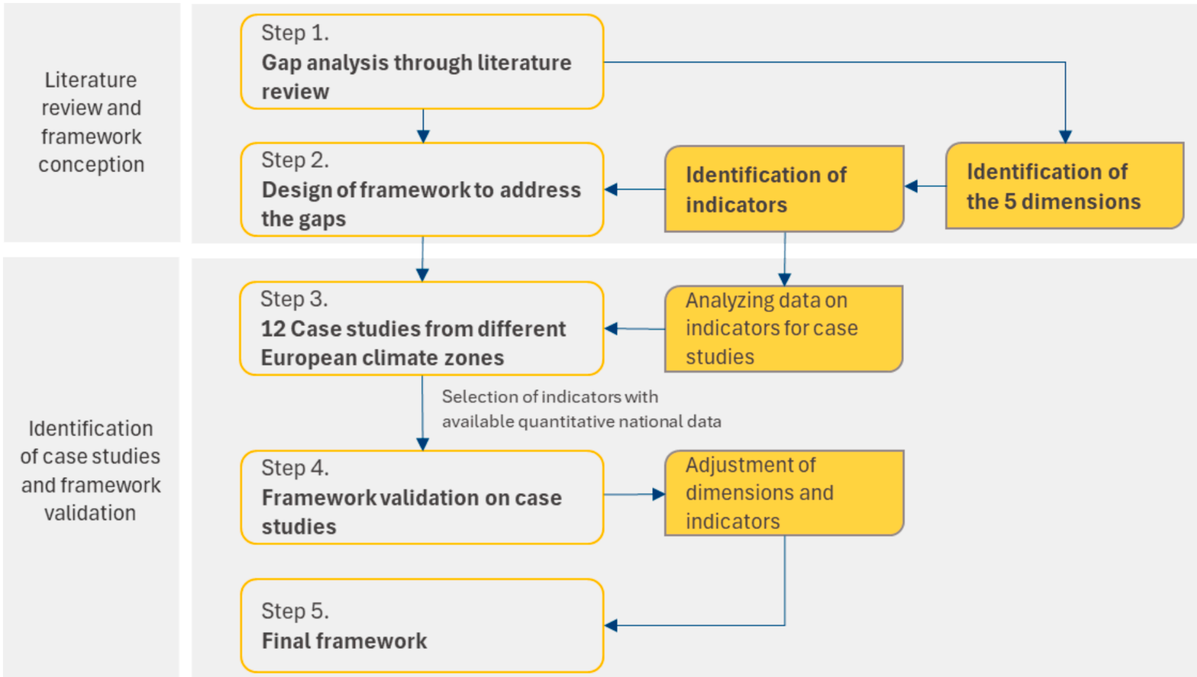

Fig. 1. Methodological steps for framework development of healthy buildings.

of their inhabitants, safeguard and enhance sustainability, and enable transformation through empowerment and resilience." This multifaceted approach aims to redefine our understanding of buildings as active contributors to both individual and collective well-being, fostering environments that promote health, sustainability, and resilience.

Hence, five key dimensions, as visualized in Fig. 2, synthesize all the components for creating healthy buildings and are as follows:

1. **Improving mental and physical health (D1)**: healthy buildings provide better physical, mental, and social health from societal, economic, and environmental perspectives via a healthy indoor climate and comfort measures.
2. **Designed for human needs (D2)**: design and understand human needs and behaviors with an inclusive and collaborative approach to fit the people using the building.
3. **Sustainably built and managed (D3)**: prioritize sustainable measures across the building life cycle, considering climate protection, resource usage, energy consumption, and carbon emissions.
4. **Resilient and adaptive (D4)**: ensure adaptability to climate changes and minimize environmental impact while being contextually adaptable to local climate zones as well as changes in building use.
5. **Empowering people (D5)**: empower people with knowledge of healthy buildings through education and communication throughout their whole life cycle.

These five dimensions collectively define the holistic concept of healthy buildings, each addressing a critical aspect of building performance and sustainability. However, focusing on just a few of these dimensions while neglecting others can lead to imbalanced outcomes. For instance, a building designed to prioritize mental and physical health (D1) and sustainability (D3) may achieve excellent indoor environmental quality and enhanced environmental impact. However, if the dimension of empowering people (D5) is overlooked, the long-term benefits of these features may be compromised. Without adequately educating and engaging occupants, the building may suffer from poor operational practices, reducing energy efficiency, compromising occupant health, and diminishing overall resilience. Similarly, a design that emphasizes human needs (D2) and adaptability (D4) might successfully address occupant behavior and climate variability, yet if it fails to incorporate sustainable construction and management practices (D3), it risks increasing life cycle environmental impacts, such as higher resource consumption and carbon emissions. Thus, integrating all five dimensions is essential to ensuring that buildings are not only healthy and sustainable but also resilient, adaptable, and capable of maintaining their performance through informed user participation and ongoing adaptability.

Each dimension, along with its respective indicators and how they contribute to the overall health, sustainability, and resilience of the building, is explained in detail in the following sections.

3.1.1. D1: Improving mental and physical health

A central component in the definition of healthy buildings is the well-being of occupants, ensuring and improving their mental and physical health. Several interacting factors impact mental and physical health, and one's mental health can impact their physical health conversely [26,96]. Abundant research on buildings and occupants highlights how several determinants of health (e.g., income, stress, noise, indoor air quality (IAQ), thermal conditions, and daylight) impact both physical health and mental health. Social, psychological, economical, emotional, and cultural aspects are all directly linked to an individual's physical and mental health [97]. Therefore, the rest of this section will refer to health when both aspects are impacted.

Healthy buildings should have two targets to achieve the highest possible health outcomes: (1) mitigating the risks associated with exposure to factors harmful to health and (2) introducing elements that improve health. From a physical perspective, indoor environmental quality (IEQ), i.e., IAQ, thermal, visual, and acoustic conditions, has a significant influence on human health, as well as on well-being and productivity [27]. Health risks in buildings are directly associated with a range of issues, notably sick building syndrome (SBS), i.e., various nonspecific symptoms, as defined by the WHO in the 1980 s. SBS can be triggered by discomforting temperatures or relative humidity levels, odors, and the presence of biological and chemical pollutants (for example, emitted by construction and decoration materials). Symptoms of SBS encompass irritation of the eyes, nose, and throat, headaches, persistent coughing, heightened light sensitivity, and flu-like symptoms

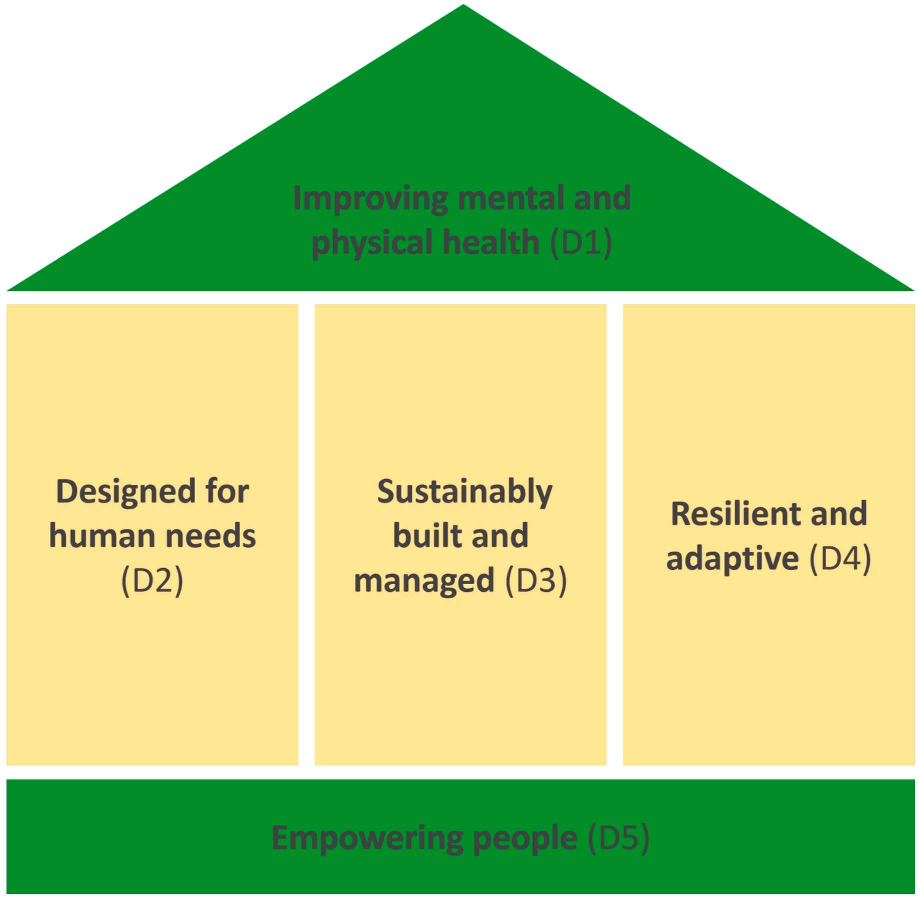

Fig. 2. Five dimensions of healthy buildings framework.

[26]. Lower levels of control over options such as operable windows or thermostats are also associated with SBS [98]. Additional health effects are associated with poor indoor conditions, such as mold, dampness, condensation, overheating, excessive cold, and various forms of pollution (both from outdoor sources like road traffic and indoor sources like chemicals from furniture, carpets, and paints) [15].

Thermal comfort is based on the individual's thermal perception, influenced by various aspects of the thermal environment such as air temperature, humidity, air velocity, human behavior such as metabolic activity and clothing level, and adaptation level, which is determined by various factors such as age, gender, geographic location, and climate [33,85] and is defined as 'the state of mind that expresses satisfaction with the thermal environment' [99]. Visual comfort refers to the sufficient amount of natural or electric light, the absence of glare, and access to views of the outdoors [100]. Daylight, in particular, plays an important role in biological processes that affect human health. For example, sleep is an important part of human health and well-being and is largely dependent on the circadian rhythm [101,102]. Studies have also linked neuroendocrine and cognitive functioning to ocular light exposure [102]. Acoustic comfort refers to the capacity of buildings to protect occupants from disruptive noise, both outdoors and indoors, and offer an acoustic environment suitable for the building's intended purpose [29].

Enhancing health can be achieved through several ways, encompassing building design, ergonomics, and behavioral adjustments. IAQ can be improved by reducing the sources of air pollutants and increasing ventilation rates [28]. Beyond those physical factors, health can be improved through nature, which can be integrated within and around buildings. Exposure to nature, like views of greenery, positively impacts health in buildings. This concept, known as biophilia [103], recognizes our innate connection to nature and aims to bring it into building design. Adding green elements to spaces, such as offices and schools [104], can boost productivity and creativity [105] and even speed up recovery for hospital patients [106]. Also, the benefits of nature extend both inside and outside building environments, underlining the far-reaching impact of biophilic design principles.

Therefore, enhancing both mental and physical health can be achieved through several ways, encompassing building design, ergonomics, and behavioral adjustments, some of which have been previously mentioned, such as improving IEQ and implementing good hygiene practices.

The COVID-19 pandemic brought about a decline in the mental and physical health of many individuals, primarily due to restricted access to green spaces and enforced isolation from others because of the lockdowns [48,49]. This impact was further exacerbated for individuals residing in substandard housing conditions [107,108]. Feeling socially connected to others is important to safeguard good mental health. Ensuring that everyone has access to green spaces and can socialize with others is therefore not just 'nice to have' boosters of health and well-being but a vital need for human beings. Added to this are the positive effects of physical activity [59]. This can be integrated as early as the design stage of a building, as well as in the wider planning of a neighborhood or city.

Another noteworthy design aspect that can significantly enhance mental health revolves around architecture's ability to craft aesthetically pleasing buildings and spaces. In ancient Greece, architecture was foremost understood to create buildings that emphasized human well-being. Today, functionality has taken precedence over beauty, with a toll on our mental health. Modern brain imaging technologies show that humans react negatively to specific architectural features (for example, sharp edges, tall steel buildings, and narrow corridors), impacting our cognitive, emotional, and neuro-psychological responses [87,89,101].

These could include feelings like fear and oppression. On the other hand, research highlights how aesthetic or affective design can positively impact mental health, creating buildings and spaces in which people like to be and thrive [109]. Architectural approaches such as biomimicry or bioclimatic design are great examples of how the indoor environmental climate, aesthetics, and integration of nature are all connected to create truly healthy buildings [19,110].

Furthermore, affordability for residents affects health and well-being. There is a crucial link between affordable housing and positive health outcomes, such as stress reduction, increased mental health, and less exposure to infectious diseases [42]. People with lower incomes are more likely to experience housing-related health disparities due to their limited ability to afford proper heating, cooling, and access to hot water and to move far from outdoor air pollution sources [37–39]. Rising fuel costs lead to direct health consequences such as asthma and Chronic Obstructive Pulmonary Disease (COPD) developing or worsening.

Table 2 presents the list of indicators of the first dimension identified from the literature and highlights the sub-indicators with their brief explanation.

3.1.2. D2: Designed for human needs

Human-centered design is a creative approach to problem-solving tailored to the needs of the end user [120]. Architecture has always been deeply rooted in what people now refer to as human-centered design. There are many ways in which this approach could be practically applied to create healthy buildings, such as user-centered design, inclusive or universal design, collaborative design, and people-centric design. As the name implies, human-centered design puts users at the heart of the design process [18]. In the context of healthy buildings, universal design is most fitting.

Universal design is a process that enables and empowers a diverse population by improving human performance, health and wellness, and social participation [16]. The seven principles of universal design were developed in 1997 by a working group of architects, product designers, engineers, and environmental design researchers to guide the design of environments, products, and communications. These were (i) Equitable Use: *when a design is useful and people with diverse abilities can use it (*e.g. *using signages for the blind)*, (i) Flexibility in Use: *when a design accommodates wide range of preferences (*e.g. *providing lift, escalator, staircase for the movement)*, (iii) Simple and Intuitive Use: *when a design is easy to*

Table 2
Key indicators to improve mental and physical health in healthy buildings (Dimension 1 of the framework).

Indicators		Sub-indicators	Explanation of sub-indicators
Indoor environmental quality (IEQ)	Indoor air quality (IAQ)	Ultrafine particles, $PM_{2.5}$ and PM_{10}	Major and well-documented human health effects [111].
		Carbon dioxide (CO_2)	Tracer of ventilation efficiency in an occupied building.
		Carbon monoxide (CO)	Concentrations below the WHO guidelines to avoid acute poisoning [111].
		Volatile and semi-volatile organic compounds (VOCs and SVOCs)	Health-based limit values for VOC and SVOC emissions from construction products indoors [112].
		Radon	Concentration below the EURATOM IAQ guideline value to prevent lung cancer [113].
		Lead	Measurement of lead to avoid exposure [114].
		Asbestos	Highest safety standards for repairs or removal of asbestos in buildings [115].
		Ventilation rate	A minimum acceptable ventilation rate [116] [.
		Clean air filtration system	Regularly cleaned air filtration systems to prevent from outdoor air pollution and from viruses and bacteria transmission.
		Damp / Mold / Condensation (DMC)	Absence of dampness, mold, and condensation.
	Thermal comfort	Indoor air and radiant temperature	The minimum and maximum indoor temperature to ensure health and well-being.
		Relative humidity	Minimum and maximum relative humidity to reduce thermal strain.
		Air velocity	Maximum values in winter to reduce draft perception Supporting minimum values in summer to reduce thermal strain
		Subjective feeling of cold or warmth	Satisfaction with the thermal environment.
	Daylight, lighting, and visual comfort	Daylight	Sufficient light levels to support image-forming and non-image-forming effects [101,102]. Limit bright areas within the visual field. Large view from the windows [117].
		Electric lighting	Sufficient levels of electric light without glare and without flickering [118].
	Acoustics comfort	Noise from outdoors	Satisfaction with the acoustic conditions (sound pressure level) of noises coming from outside the building, such as street noise.
		Noise from within the building	Satisfaction with the acoustic conditions (sound pressure level, reverberation) of noises coming from within the building (both from occupants and mechanical systems).
Connectedness to nature		Time spent outside nature in nature	Amount of time spent per day/month/year in nature, such as a park, lake, or forest.
		Satisfaction with nature within and around buildings	Satisfaction with the type of nature (blue or green) directly around the building and in the neighborhood and with the access to outdoor spaces for physical activities.
Social connections		Within community	The opportunity to be a meaningful part of the community.
		With close relations from private and professional spheres	Meaningful connections with family, friends, colleagues, and others (such as patients in a healthcare setting).
Design appeal		Affective design	Affective design encompasses the neuro-psychological, cognitive, and emotional responses to architecture and design, including considerations such as colors, edges and contours, placement of objects/structures, and surface materials and textures, all of which impact occupant morale and mood.
Affordability		Household disposable income	The EU defined Household disposable income as “the total amount of money households have available for spending and saving after subtracting income taxes and pension contributions” [119].
		Operating and maintenance costs	The costs of water, electricity, and heating/cooling and maintenance of water, electricity, and heating/cooling systems of a building are incurred throughout the useful life of a building.

*understand, regardless of the user's experience, knowledge, language skills, or current concentration level (*e.g. *exit, entry information)*, (iv) Perceptible Information: *when a design communicates necessary information effectively to the user, regardless of ambient conditions or the user's sensory abilities (*e.g. *display of warning signs)*, (v) Tolerance for Error: *when a design minimizes hazards and the adverse consequences of accidental or unintended actions (*e.g. *a software program allows resetting to normal setting if an inappropriate selection is made)*, (vi) Low Physical Effort: *when a design can be used efficiently and comfortably, and with a minimum of fatigue (*e.g. *use of automatic doors)*, (vii) Size and Space for Approach and Use: *when a design provides appropriate size and space for approach, reach, manipulation, and use, regardless of the user's body size, posture, or mobility (*e.g. *adjustable tables, seating)* [17].

Developers have realized the huge potential of human-centered design; thus, in real estate projects, they consider three main performance metrics: (1) Physical activity: design to promote physical activity for people living in high-rise or constrained spaces. (2) Safety and community: shared spaces where people and their neighbors can create a safe, inclusive, and supportive community. (3) Quality of life: quality of the time people spend with their families, friends, and even strangers within the surroundings and the types of activities they engage in [79]. Virtual connectivity has many benefits for productivity and quality of life. In the digital world without face-to-face interactions, human-centered design has the capability to mitigate negative outcomes by giving more opportunities to interact with neighbors.

Design for human needs can also help when user needs change or when users change. These needs could include disabilities or age-related adaptations to a building, the need to work from home instead of an office, or a different layout in schools or hospitals. Sometimes, these changes extend to the entire building, for example, when an office building is converted into apartments. International standards can be used as guidance, such as ISO 9241–210 'Ergonomics of human-centered system interaction' which describes the human-centered design as an 'approach to systems design and development that aims to make interactive systems more usable by focusing on the use of the system and applying human factors/ ergonomics and usability knowledge and techniques' [121]. The standard specifically recommends six characteristics:

(i) The adoption of multidisciplinary skills and perspectives to benefit from creativity and collaboration
(ii) Explicit understanding of users, tasks, and environments of different stakeholder groups
(iii) User-centered evaluation-driven/refined design through feedback from users
(iv) Consideration of the whole user experience, considering all appropriate impacts
(v) Involvement of users throughout design and development
(vi) An iterative process to better functionality from a user perspective and mitigate risk

Therefore, human-centered design has added value that promotes the creation of healthy buildings by understanding human behavior and influencing it. It could be used as a co-creative process through user-engagement that could be applied to new and existing buildings with different stakeholders to achieve a collective vision for healthy buildings as well as surrounding spaces. Additionally, the concept of a community and sociable environment in designed spaces is important for meeting fundamental human needs. It positively impacts mental health by reducing loneliness, supports physical well-being through outdoor activities, and contributes to stress reduction. It also fosters a sense of security, provides vital support systems, and offers cultural and economic enrichment. By creating spaces that prioritize community and inclusivity, we can enhance overall well-being and create healthier and more sustainable environments for all.

Furthermore, the integration of smart or automated features promotes energy efficiency while providing residents with personalized control options that align with their lifestyles, thus creating a harmonious and health-conscious living environment satisfying their needs and requirements.

Table 3 presents the list of indicators of the second dimension identified from the literature and highlights the sub-indicators with their brief explanation.

3.1.3. D3: Sustainably built and managed

Sustainably built and managed means achieving more with less. It is the management of the human use of natural resources to provide the maximum benefit to current generations while maintaining the capacity to meet the needs of future generations [122]. Sustainably built and managed buildings, whether these be new builds or renovations, must have a consistent approach to design, construction, operation, and use throughout the life cycle of the building. This approach could be anchored into three main areas that stimulate a sensitive use of our existing natural resources: (i) Bio-climatic design: responsive to the bioclimatic environment where the building must respond to the local environment and blend into the natural surroundings and bio-diversity using techniques such as passive heating or cooling [123]. (ii) Operational performance: achieving high operational performance (functional and technical performance) through energy efficiency, low carbon emissions, water conservation, and a satisfactory indoor environment [124]. (iii) Circularity: selection of sustainably sourced materials, minimizing natural resource consumption, and environmental impact of buildings by reducing waste and keeping products and materials in use through recycling and recovery, inducing lower embodied emissions throughout the whole life cycle [125].

The above three strategies encompass a complete perspective of the sustainability of non-renewable resources that occur from design to cradle for buildings. However, these could also be classified into more generally known strategies, namely energy, material, and water conservation [126]. As such, renovation projects, which are limited in their ability to change existing conditions, such as layout or orientation towards the sun, can still be sustainably built through energy, material, and water conservation measures. In some instances, it is even possible to change the design of existing buildings to increase energy, material, and water conservation [21].

The use of energy is an important environmental issue, and buildings are undoubtedly among the largest consumers of energy. Buildings consume energy during the life cycle for both operational and embodied energy. Operational energy is the energy used to fulfill the activity for which the building is used and maintains a comfortable environment within buildings, and can account for about 80–95 % of the total energy consumption as well as CO_2 emissions [127]. It includes heating, cooling, ventilation, hot water, and sometimes appliance usage. Embodied energy is the total energy used in the creation of the building and end-of-life, including indirect (material extraction, processing, manufacturing, transport, and construction) and direct processes (construction and assembly). Thus, energy and material conservation aims to reduce the use of fossil fuels and increase the use of renewable sources, resulting in lower operational and embodied carbon emissions.

The use of natural resources for building materials through raw material extraction and production has a direct impact on the environment, i.e., on the biodiversity and natural ecosystems that then support or reduce human health and well-being. The use of non-renewable materials should be reduced, and the selection of materials should be made at the initial design phase to reduce the impact of material consumption on the environment, thus achieving better material efficiency with methods such as focusing on waste reduction and using natural and local materials. Re-purposing buildings, for example, for change of use, can also save on construction materials and thus embodied carbon. Further materials to consider are those used for complex automation systems, where resource usage of installation, operation, maintenance, and reusability need scrutiny.

Table 3
Key indicators for human needs in healthy buildings (Dimension 2 of the framework).

Indicators	Sub-indicators	Explanation of sub-indicators
Universal design	Equitable design for all users	Making sure that the usability of the design is equal for all users, including those with a mental or physical disability, older persons and children through either an identical or similar process.
	Flexibility in use	The design should incorporate flexibility for use in differing ways – whether this be based on needs, preferences, or requirements based on ability or mobility.
	Simple and intuitive use	The user should be able to understand the design and use it easily regardless of ability, age, language, mobility, etc.
	Perceptible information	The design should provide any required information to every user in all situations. The use of pictures, both verbal and tactile, provides information clearly.
	Minimal risks and hazards (Tolerance for Error)	The safety features of the design should incorporate features to minimize risks and hazards, aiming for a foolproof design.
	Low physical effort	The design allows the user to operate without unnecessary physical effort or fatigue at a normal or comfortable position.
	Size and space for approach and use	The design should allow for approach and use and be suitable for different heights, sizes, and ages.
Human-centered interaction	User engagement in the process	The design should be informed through a collaborative process with stakeholder involvement.
	Involvement of multi-disciplinary skills	The design process should involve different disciplines and perspectives.
Community design	Community and sociable environment	The built environment surrounding the designed spaces must incorporate aspects that promote socializing for the building community.
Intelligent building design	Smart or automated features (Lighting, HVAC, domestic hot water)	Integrated smart features, including adaptive lighting for healthy illumination, temperature control for optimal comfort and energy efficiency, and personalized scheduling, such as heating water during specified times without reducing individual control options.

Depletion of water resources is a known environmental issue. Water is consumed not only in building construction and operation but also in other life cycle stages of extraction, production, manufacturing, and delivery [128]. Methods to reduce water consumption must be used from design to operation phases, minimizing the consumption of this precious resource. Water management also refers to ensuring the safe supply of drinking and hot water to the building, considering materials used for water pipes and safe storage facilities for hot water.

For all three strategies, sustainable management techniques that ensure high-quality processes throughout the lifetime of a building need to be employed; these could include a building protocol with periodic quality control checks but also encouraging workers to mention faults and snags so they can be immediately remedied [129]. In addition to its environmental benefits, sustainably built and managed buildings offer significant cost savings [126]. This has become particularly relevant with recent price increases for the building industry [130]. This poses a risk, especially to buildings owned or rented by social actors such as non-profit housing organizations, government agencies responsible for public housing, and community development corporations, which may struggle to afford deep renovations or construct new buildings to ensure healthy buildings. The State of Housing Report 2023 by Housing Europe highlights that the increasing unsustainable costs for construction and renovation, with the added increasing costs of financing, lead to many renovation projects being delayed or dropped [131]. The resulting job losses, precarious employment, and reduced income for companies can lead to detrimental health effects for staff [132]. The current annual renovation rate in Europe is about 1 % – A recent study by BPIE estimates that the renovation rate needs to be at least 3 % per year for the EU to meet its climate targets [133].

Some innovative solutions have been proposed to ensure a sustainable building sector, especially regarding deep-scale renovations [134,135]. Through energy-efficient practices, water conservation measures, material efficiency, and effective waste management strategies, building owners can reduce utility expenses, minimize maintenance and repair costs, and efficiently manage waste disposal. Whilst these approaches to reduce the environmental impact of buildings have positive effects on overall planetary health [13,14], the main aim of the sustainably built and managed dimension is to impact human health through reduced resource use and lower environmental impact of processes and materials throughout the life cycle of a building.

Table 4 presents the list of indicators of the third dimension identified from the literature and highlights the sub-indicators with their brief explanation.

3.1.4. D4: Resilient and adaptive

Resilient and adaptive buildings can deal with outside environmental forces that impact health, such as natural hazards and the consequences of climate change. Two kinds of actions can be taken: (1) building components and structures integrate or add elements that withstand natural hazards and extreme weather events, such as earthquake-safe building structures or hail-resistant windows. (2) Buildings can integrate or add elements that help restore ecosystems and mitigate against climate change consequences. Integrating greenery on or near buildings to cool the air and store water [136] or solar shading to reduce overheating [137] are examples here. More positive co-benefits – reducing the risk of flooding, better air quality, comfortable ambient temperatures – can be achieved if many different actions are implemented together [138], e.g., cooling an urban area through ecosystem restoration while installing solar shading.

Climate trends and projections indicate several changes on the global and local scales. The latest World Meteorological Organization (WMO) report from 2022 [139] shows that Europe is breaking record heat waves, leading to at least 15,000 excess deaths in the summer of 2022. In cities, the urban heat island effect is a serious health risk, leading to circulatory problems and even heat deaths [140]. Europe has four main climate zones with sub-zones (Subtropical climate – maritime/intermediate/continental; Cold climate – maritime/ transitional/intermediate/continental; Warm climate – maritime/transitional/intermediate/continental; Circumpolar – subpolar/polar) with most of the building stock located within the subtropical, cold, and warm climate zones [141]. For each of the climate zones, building design must be adapted to the local context. The ability of a building to be resilient and adaptive will depend upon existing conditions. For renovations, a building is limited in terms of its location (orientation towards the sun, wind and rain exposure, street noise), and only a few elements could be improved as a result (e.g., external paint, roof/wall insulation). For new builds, while existing structures are less of a constraint, national building regulations will need to promote an optimal resilient and adaptive building.

Table 4
Key indicators for sustainably built and managed healthy buildings (Dimension 3 of the framework).

Indicators	Sub-indicators	Explanation of sub-indicators
Energy and carbon emissions	Passive heating and cooling	Taking advantage of natural processes such as conduction, convection, and radiation to warm or cool a building reduces the need for energy-intensive heating or cooling systems.
	Energy-efficient systems and technologies	Reducing energy demand and improving energy reliability through measures of energy efficiency.
	Operational energy	Measures to reduce operational energy demand in buildings throughout the life cycle of the building using passive and active design methods.
	Embodied energy	Measures to reduce the embodied energy and carbon footprint associated with building life cycle stages, from construction to demolition.
Material and circularity	Bio-based materials	Specification of local, natural, and durable materials.
	Reuse/Repurpose, recycle and reduce materials	Buildings with durable, non-toxic materials that are efficient and flexible extend the life of materials through reuse, repurpose-recycle, and reduction of building components.
	Design for waste minimization	Methods for reuse, recycling, storage, and disposal of construction waste.
Water	Water efficient systems	Using water-efficient plumbing fixtures to minimize wastewater.
	Water recycling and reuse	Using wastewater recovery methods.
	Greywater retention	Collection of grey water and other non-potable water for on-site use.
Management	High-quality maintenance of buildings and technologies	Quality maintenance by occupants and repair service of the building in general and systems/technologies installed.
	High quality of construction throughout the life cycle of the building	High-quality workmanship during all stages of a building's construction, whether new, renovated, or demolished.
	Waste management	Effective waste management strategies, including recycling and composting programs, to minimize the generation of waste and reduce landfill contributions
	Material costs of production	Costs relating to the production of materials.
	Costs of construction	Costs relating to the construction, demolition, change of use, and renovation of building projects.
	Labor costs	Labor costs of building projects.

Resilient cooling systems encompass both active and passive approaches as well as hybrid approaches [142,143]. Active cooling systems involve mechanical components like air conditioning to regulate indoor temperatures efficiently. With more heat waves, enhanced electricity grid conditions are needed to ensure resiliency to avoid blackouts, which would increase mortality rates when these active cooling systems do not work [144]. In contrast, passive cooling systems rely on architectural and natural elements, such as shading and ventilation, to maintain comfortable indoor conditions without excessive energy use. These systems are crucial in promoting climate resilience, especially in the face of increasing environmental challenges. They are essential components in designing and managing buildings that can withstand and adapt to changing climatic conditions.

Not only can buildings and their structural aspects be changed, but the environment around buildings can also benefit from measures to mitigate and adapt to changes in the climate. Nature-based solutions (NBS) are a group of measures aiming to incorporate green and blue infrastructure and measures into dwelling areas – mainly urban areas, as these have insufficient green and blue infrastructure to adequately deal with extreme events such as heat, flash floods, or cold. Ideas such as the 3–30-300 rule are being proposed [43] – at least three well-established trees in front of every building, no less than 30 % tree canopy in every neighborhood, and no more than 300 m to the nearest public green space – this would have positive impacts on both the mental and physical health of residents, as explained in the mental and physical health dimension.

Resilience can also come from building users themselves. Schweiker [34] postulates that, especially around thermal comfort, the focus can be shifted from relying on buildings' performance only towards encouraging human resilience and adaptation to thermal conditions. This is of particular importance, considering that our ability to deal with thermal changes is limited [54]. Spending time outside our thermal comfort zone can enhance human thermoregulatory capacities and thermal resilience and improve cardiovascular and metabolic health [54,145]. Therefore, human resilience and adaptation to indoor thermal conditions could help save energy and resources while enhancing our physical health.

Resilience and adaptation of buildings can be supported through automation and smartness, especially those smart features that target optimal energy use and performance and adaptation to signals from the grid. Automation can help deal with the possible conflict between strategies focused on energy consumption reduction and those focused on the health and comfort of the indoor environment [146]. Three interdependent factors influence the quality of interactions between the built environment and the occupants: i) building design and construction (passive design/active technology), ii) occupant (information/control/behavior/occupancy), iii) indoor environmental quality (management of indoor environment controls/energy efficiency).

Smartness can be extended to *neighborhoods and districts*, even *national and international scales,* for example, through utility supplies. In neighborhoods or districts, the energy grid connecting buildings could be connected and energy distributed in the most efficient way [44]. This would allow communication between buildings, neighborhoods, and districts, and if focused on health aspects, could improve the overall health of building occupants and their communities [59].

However, any automation introduced in a building needs to be considered for its necessity and possible side effects. To give a few examples: (1) related to D2, automation should not reduce individual control opportunities for occupants. (2) Smart meters need to ensure that poor households are not disadvantaged by changes in their metering arrangements [40]. (3) Electromagnetic field radiation (EMFR) also needs to be considered when installing automation products that rely on radio, Wi-Fi, or satellite connections, as specifically extremely low frequency and radio frequency still raise concerns regarding their effects on human health, including to the brain, nervous, and cardiovascular system [147]. Additionally, excessive automation can lead to higher embodied carbon and greater environmental impacts due to the resources required for its production and installation. Solutions exist for how architects and designers, as well as other stakeholders in the building industry, can ensure that the impact of EMFR is reduced or eliminated where possible [147].

Resilient and adaptive buildings need to be able to respond to emergencies, such as power outages, fires, intrusions, or health emergencies. These response options could entail different features for a variety of building types – a large retail building or hospital might

Table 5
Key indicators for resilient and adaptive healthy buildings (Dimension 4 of the framework).

Indicators	Sub-indicators	Explanation of sub-indicators
Resilient to natural hazards	Earthquake-proof	Structure of a building (e.g., structural frame, foundation) that can withstand earthquakes with minimal to no damage.
	Severe weather conditions protection	Measures to protect or resist flood/hail/rain/snow/storms/heatwaves to reduce damage to buildings (e.g., storm-hardening).
Resilient systems	Integrated resilient cooling and ventilation systems	Active (mechanical) and passive (natural) cooling methods to adapt to climate change, ensuring occupant comfort and well-being.
Blue and green infrastructure	Blue infrastructure	Outside infrastructure that provides water features for cooling the air and acts as water retention.
	Green infrastructure	Outside infrastructure provides greenery for cooling, cleaning the air, restoring ecosystems, and water retention through permeable surfaces.
Smart or automation services	Dynamic building envelope	User-specific smart features, such as solar shading, blinds, and locks, provide safety and optimal indoor environmental quality.
	Power management	Adjustment of electricity consumption/storage based on grid load.
	Monitoring and control	Smart services are based on monitoring the health of users, with users in complete control of such features.
	Emergency response	Control elements that alert users, building owners, and emergency response services in case of an emergency.

benefit from integrated automated features that send out visual and acoustic alerts as well as directly respond to fires through sprinkler systems, whereas a rural single-family home might only require battery-powered fire and carbon monoxide alarms.

Table 5 presents the list of indicators of the fourth dimension identified from the literature and highlights the sub-indicators with their brief explanation.

3.1.5. D5: Empowering people

Every building consists of a range of socio-material arrangements, such as production materials, construction process, use, and end-of-life, throughout its life cycle [148]. In each arrangement, different people create and maintain the health of buildings, people, and the environment. Building users play a significant role, as residents, staff, school children, nurses, doctors, or patients can all improve their own health, that of others, and of the buildings in which they live, learn, work, or recover.

People need the know-how to create and maintain healthy buildings. However, studies have highlighted a lack of skills and knowledge in the building industry, particularly in terms of sustainability and circular economy principles [149]. A large-scale survey carried out with the UK buildings supply chain found that standard contractors for maintenance in social housing often do not know how to carry out retrofit works [150]. Further studies across Europe found a lack of knowledge on zero carbon housing from occupants, the build team, design team, maintenance team, and planners, and the lack of skilled labor as major barriers [151], as well as the industry being only in the early stages of developing circular economy practices [3]. In scientific research, especially circular product design, end-of-life considerations that include modular integrated construction, quality, economics, and holistic performance assessment tools are receiving little attention [89].

Lack of clear communication has also long been a major barrier in the building industry [152]. This extends to communication within a single organization and between stakeholders along the supply chain and end users of buildings. However, clear and effective communication is key to healthier buildings, as users often lack knowledge of how to use technologies installed in homes or offices [153], and when things break down, maintenance and repair are simply reactive rather than consistently trying to increase the longevity of products and technologies. These facts highlight the importance of good communication and effective education and training to ensure the best use of buildings; in short, empowering people through knowledge. As the EU Levels Framework highlights, training and education towards a more circular construction industry is an important pillar to change the status quo. This training and education would target all stakeholders in the building industry, from production to demolition and reuse [154].

Smart technologies have the potential to empower users, as the EU views smart buildings as being able 'to sense, interpret, communicate, and actively respond efficiently to changing conditions' [155]. A building, especially when it contains different modern technologies that regulate heat, water, lights, and safety aspects, creates heavy demand on occupants – people need to know how each part of the system works for it to be effective, fulfill needs and preferences, and to keep maintenance low. Smartness and simplicity can help in optimizing each part of the system, be that through technologies, connectivity, or information and guidance, and help in running different parts effectively to maximize their health impact. Smart technologies can be adapted to specific building types, which is particularly important in terms of safety – as such, a hospital or office might need access control features, and an elderly residential home might need security cameras for entrance doors.

Empowerment can take place throughout the different phases of a building's life. The first phase is the conceptional phase – here, designers, architects, and planners, as well as producers of building materials, can be empowered to create buildings (and materials) according to evidence on what makes a truly healthy building. This includes the choice of location of buildings, where this is possible, to ensure optimal bioclimatic conditions [19,123], as well as the direct involvement of later user groups to account for their needs. In the second phase, buildings are constructed or renovated, with the construction industry as the main stakeholder benefiting from changes to their skills and knowledge set. The use of a building is the third phase, where both users and maintenance and repair crews can be empowered to keep buildings healthy. Lastly, buildings can change their use or be demolished, and companies specializing in those aspects can integrate healthy building aspects into their knowledge and skill sets.

For users, empowerment can entail how they use energy in their homes. Low-cost solutions such as keeping temperatures at the minimum comfort level in winter (when not in the situation of fuel poverty) and installing solar shading to reduce indoor temperatures in the summer would especially help residents struggling with income. Re-evaluating material consumption can also be empowering; research increasingly shows that material possessions actually decrease well-being [156,157]. Available control opportunities of systems and technologies within a building can also empower users in all types of buildings, but especially in their own homes [20]. As the dimension of mental and physical health shows, being healthy includes having meaningful social connections [50]; we get more positives out of connecting with others than by consuming material goods. It is then a lucky by-product that consuming fewer materials also has positive effects on nature and leaves more disposable income. Effects such as the spillover and rebound effect [158] could be minimized if users are aware of the positive effects of social connections and fewer material possessions.

With technological advances for measuring or monitoring building performance, it is necessary to ensure any data collected remains fully in the control of the building owner (or where it is a residential building, with the residents). Building owners and residents should decide how and with whom data on both buildings and behaviors is shared, for example, when a third party monitors or provides analyses on data.

Table 6 presents the list of indicators of the fifth dimension identified from the literature and highlights the sub-indicators with their brief explanation.

3.2. Validation of the framework on case studies

In order to validate the framework with the indicators and sub-indicators, 12 case studies in 8 countries of different building types (public, commercial, residential) were identified. The validation process included five new buildings and seven renovation projects mapped against the framework using both qualitative and quantitative data. The case studies were chosen based on good practice, and the aim was to cover the major climate zones of Europe for their representativeness and to demonstrate approaches suitable for different climatic conditions [141]. Table 7 shows details for each of the case studies.

The validation process revealed that information on implementation measures was readily available for many of the indicators and sub-indicators. However, notable gaps were identified, particularly for the first dimension, "Improving Mental and Physical Health," where data for sub-indicators related to indoor air quality and social connections was insufficient. In the second dimension, "Designed for Human Needs," which encompasses numerous qualitative aspects, initial challenges in data provision were mitigated through a second iteration. This iteration included more detailed explanations of the indicators, which facilitated the provision of the required information. The third dimension, "Sustainably Built and Managed," and the fourth dimension, "Resilient and Adaptive," were completed without significant issues. For the fifth dimension, "Empowering People," there was a discrepancy in the interpretation of the "Skills and Knowledge" indicator. This discrepancy required further clarification to ensure consistent understanding and reporting. The remaining gaps where no implementation measures were associated with an indicator were treated as unfulfilled.

The consolidated scoring is illustrated in Fig. 3. The highest scoring dimensions across all case studies are:

- **Dimension 1**: Improving Mental and Physical Health (Score: 9)
- **Dimension 2**: Designed for Human Needs (Score: 9)

The lowest score was observed in:

- **Dimension 4**: Resilient and Adaptive (Score: 6)

This analysis highlights areas where buildings perform well and identifies dimensions requiring further attention to improve overall performance. For example, all case studies included strategies to improve indoor air quality (Dimension 1), and several case studies have used recycled building materials or reduced the consumption of building materials (Dimension 3). Improvements were observed in relation to increasing building resilience to future climatic events – very few case studies included blue and green infrastructure or adaptation measures to the exterior or interior of buildings (Dimension 4). To illustrate this further, the dimension scores for a single case, Venlo city hall in the Netherlands, are shown in Fig. 3 as well (see the Healthy Buildings Barometer for further case study details [171]). For this case study, the highest score was achieved for Dimension 2.

Venlo City Hall is one of the Dutch case studies included in this study, which has received attention for its positive effects on employees [172]. The aim of this newly built public building was to provide a "pleasant and healthy workplace for employees of the municipality of Venlo" [173]. Below are key facts about the building (see Table 8), and Fig. 4 shows pictures of the outside and inside of the completed building.

The case study scores high on most of the dimensions, as shown in

Table 6
Key indicators for empowering people in healthy buildings (Dimension 5 of the framework).

Indicators	Sub-indicators	Explanation of sub-indicators
Skills and Knowledge	University courses and degrees/apprenticeships schemes / further education and continuous training across the professional life	Courses and degrees that integrate all the basic elements of health components in existing degrees and/or offer new degrees in healthy buildings.
	Information material	Material that integrates all the basic elements of health components, specific for stakeholder groups, e.g., instruction manuals, user guides, videos, social media posts, and website articles.
	Case studies	Specific examples or case studies illustrate the challenges faced due to the knowledge gap and the positive outcomes that can be achieved with proper education and skills development.
Effective communication among stakeholders	Within and between stakeholder groups	Effective communication within a single stakeholder group, such as a construction company, as well as between different stakeholder groups, including government agencies, educational institutions, industry associations, and advocacy groups.
	Multiple communication channels	Appropriate communication channels (emails, newsletters, info sheets, phone calls, meetings) for diverse audiences.
Occupant behavior and control	Occupant heating/ventilation behavior	Sufficient adaptive opportunities for the occupants to gain control over IEQ conditions themselves lead to high perceived control.
Information access and sharing	Behavioral/health data	Only building owners and users own data collected about their behavior and choose whom they want to share the data with.
	Building data	Only building owners and residents have ownership of data such as data from sensors, energy usage, temperature control systems, security systems, and other building-related information and can choose who they want to share it with. For instance, building owners may choose to share energy usage data with utility providers for billing purposes, while residents may choose to share security system data with a third-party monitoring service for enhanced safety.

Table 7
Case studies by country, climate zone, and building type.

Country	Major Climate Zone	Building Type			Building Details
		Public building	Office/ Commercial building	Residential building	
Denmark	Temperate warm – maritime	●			School (renovation) [159]
				●	Single-family building (new build) [160]
France	Temperate warm – maritime	●			School (new build) [161]
				●	Multi-family building (renovation + extension) [162]
Germany	Temperate warm – transitional	●			Music academy (renovation) [163]
				●	Single-family building (renovation) [164]
Netherlands	Temperate warm – maritime	●			Town Hall (new build) [165]
				●	Multi-family building social housing (new build) [166]
Belgium	Temperate warm – maritime			●	Single-family social housing (renovation) [167]
Slovakia	Temperate warm – intermediate			●	Single-family building (renovation) [168]
Spain	Subtropical – continental		●		Market Hall (renovation) [169]
Sweden	Temperate warm and cold – transitional			●	Office (new build) [170]

the radar diagram in Fig. 3. Innovative elements incorporated in each of the dimensions include:

- **Dimension 1 – Improving mental and physical health:** A greenhouse on the roof is connected to an air purification system that provides fresh air to the inside of the building. Ventilation is provided through a vide structure. Daylight is maximized through large ceiling-to-floor windows that allow daylight to reach far into the building. A longitudinal study following the employees of the city hall before and after the move to the new building found significant improvement in the health and well-being of employees, such as fewer sick days measured through a reduction in absences due to sick building syndrome and better perceived environmental conditions [172].
- **Dimension 2 – Designed for human needs:** Employees filled out a survey before the design was completed in order to ensure their needs were being met. The building includes many opportunities to rest and socialize, as well as stay active using staircases.
- **Dimension 3 – Sustainably built and managed:** The building follows the cradle-to-cradle principle by using materials that can be repurposed at the end of their life. Each material used was defined and has an intended pathway of usage. A water maintenance system that collects rainwater re-uses greywater, and can treat blackwater, was installed, as well as renewable energy in the form of solar photovoltaics and solar panels. Blue and green infrastructure were added in the form of an inner courtyard with a pond and vegetation, green walls both inside and outside, and a greenhouse on the roof.
- **Dimension 4 – Resilient and Adaptive:** The green infrastructure was installed to manage excess water during heavy rains, and passive cooling strategies through the vide structure and a solar chimney help keep occupants cool during hot days.
- **Dimension 5 – Empowering people:** The design team received extensive training on the cradle-to-cradle principles before designing the building. A detailed construction process was created with KPIs for four main aspects: enhancing air and climate quality, integrating renewable energy, defining material and their intended pathway, and enhancing water quality. After completion, the city hall features displays so that employees and visitors can read about the building and the associated benefits to people and the environment.

3.3. Link between indicators/sub-indicators and quantitative data at the national level

The validation of the framework also included the data matching exercise using EU-wide empirical datasets to track data availability over time. Since data gaps are large between the indicators and associated data, the figures show available data for indicators on the first dimension. Data are shown from 2015 to the latest available date as a means to track progress on these indicators since the Paris Agreement – a legally binding international treaty on climate change – was signed at the United Nations Framework Convention on Climate Change (UNFCCC) in Paris, France, in 2015 and enacted in 2016 [174].Fig. 5 provides an example of how data could be tracked for indicators in the first dimension of the EU-27. Data can also be analyzed per country. To follow the Venlo city hall case study example, Fig. 5 also shows the same five datasets as above for the Netherlands. These examples of data tracking can be expanded over time as data collection and its quality increases.

For acoustic comfort, indoor air quality, lighting, and visual comfort, no improvements were observed. Affordability had improved from 2015 until 2021, but the number of people struggling with disposable income rose again in 2022. Thermal comfort remained at the same level until 2021, with more people unable to keep their homes adequately warm in 2022.

Table 9 shows how indicators and sub-indicators are linked, along with details about how often data is collected and the latest year it was updated. Each row includes the dimension, indicator, sub-indicator, data collection frequency, and the most recent update year. This overview helps to identify data gaps, pinpoint where data collection is missing, and highlight areas where missing data prevents the

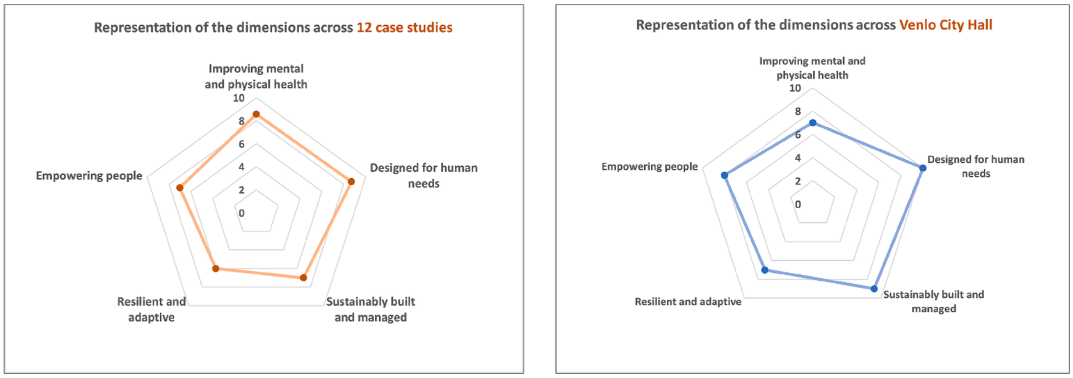

Fig. 3. Scores for each dimension averaged across the 12 case studies combined and in the Venlo city hall case study.

Table 8
General characteristics of the Venlo city hall case study.

Building Type	City Hall
Year of Construction	2012–2016
Location	Venlo, Netherlands
Building Size	27,700 m^2
Energy Class	A+
Project Lead	Municipality of Venlo / Kraaijvanger Architects

quantification of certain indicators. This analysis showed that data for about half of the indicators is unavailable. For the remaining half, 40 % have incomplete datasets. Consequently, only 30 % of the required data can be reliably tracked over time. For instance, indicators such as 'ventilation' or 'information access and sharing' lack associated data entirely. Other indicators, like thermal comfort (measured as overheating), have only been surveyed once across all Member States, with the most recent survey dating back to 2012. In some cases, for example, for indoor air pollutants and for universal design, available datasets do not match the indicators exactly. Here, proxy datasets related to the indicators were used. Since indoor air pollution is not measured and collected at the EU level, outdoor pollution was used. For universal design, overcrowding was used to exemplify the need to create spaces that fulfill people's needs, while – as shown above – universal design includes many more elements. Finally, the initial list of 69 indicators and sub-indicators, detailed in sections 3.1.1 to 3.1.5, was consolidated into a final list of 24 indicators.

4. Discussion

4.1. Findings and recommendations

The findings of this study are discussed in the following order: first, the validation process of the indicators is discussed, followed by case study findings. Lastly, issues with datasets and indicator matching are discussed. The section finishes with recommendations applicable to different stakeholders around healthy buildings.

The validation process of the framework through case studies showed that it is possible to assess existing building projects based on each dimension. However, it was not possible to find information on each of the initial 69 sub-indicators. In some cases, measures relating to indicators or sub-indicators were not recorded. For example, in Dimension 5, skills and knowledge or communication channels, as well as behavioral data, are often not recorded by those involved in the planning or execution of building projects. In other cases, measures were excluded due to cost, time, or lack of applicability issues. For instance, buildings in Denmark do not need to be earthquake-proof; smart or automated services were not desired by some homeowners; water recycling was too costly in some existing buildings.

While the framework proposed in this paper is designed to be universally applicable across all building types, it is essential to recognize that the specific performance targets for various indicators may differ depending on the building's function, occupancy, and environmental context. For instance, thermal comfort levels might vary between residential and commercial buildings due to the differing adaptive opportunities available to occupants. In residential buildings, individuals have more control over their immediate environment—such as adjusting windows, curtains, or personal fans—allowing for a broader range of acceptable thermal conditions. Conversely, in office buildings, the thermal environment typically needs to be more consistently maintained to ensure occupant productivity and comfort, leading to stricter performance targets. Similarly, lighting levels required for optimal visual comfort may differ between educational buildings, where tasks like reading and writing are prevalent, and healthcare facilities, where lighting must balance comfort with the need for precise medical procedures. Furthermore, the acceptable range for IAQ parameters might vary between industrial and residential buildings, given the differences in pollutants present and the health risk profiles of the occupants. These variations underscore the necessity of tailoring performance targets for each indicator and sub-indicator to the specific building type and application while still utilizing the universal framework presented here. This approach ensures that the framework remains flexible and adaptable to the diverse needs of different buildings, providing a robust structure for improving mental and physical health, sustainability, and resilience across the built environment.

The case study findings also showed that some indicators are harder to assess than others. In some cases, such as in Dimension 2, indicators were implicitly considered in case studies yet often not explicitly written down in documentation, similar to those in Dimension 5, where activities such as staff training are carried out but not documented in a systematic manner. It is therefore recommended that documentation relating to healthy building projects consider the indicators of the five dimensions early during the process, ideally at the beginning of the design process. This procedure would ensure that information is recorded as completely and comprehensively as possible.

One of the main goals of the case study validation was to test whether the framework can be applied to see how buildings perform against the indicators and dimensions. The individual analysis, as exemplified by the Venlo city hall case study, can be used to identify weaknesses and determine where improvements are needed. Similarly, the consolidated scoring, as shown in Fig. 3, serves the same purpose. The score per dimension indicates which dimensions score high or low, and then each individual indicator can be targeted for improvement. Here, it is important to mention that different measures can serve the same function – for example, ventilation can be improved both through manual and technical measures.

Many measures implemented in the case studies satisfy more than one indicator (or sub-indicator) – for example, the greenhouse on the Venlo city hall roof is a measure of green and blue infrastructure,

Fig. 4. Photos from the completed Venlo city hall. Image .
Source: C2C Venlo. Used with permission. https://c2cvenlo.nl/media/

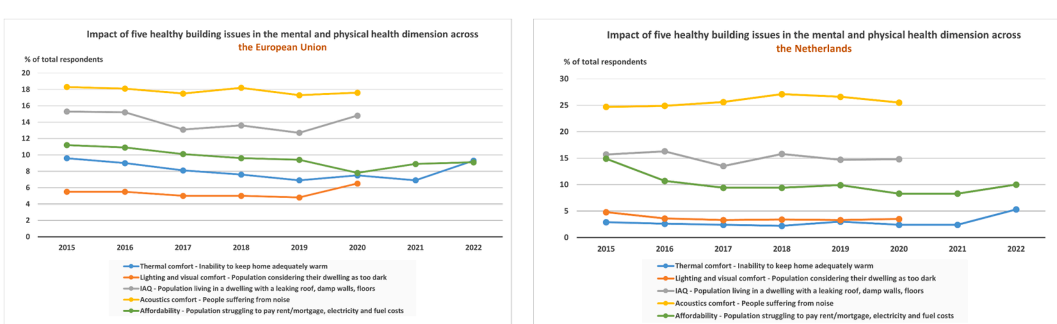

Fig. 5. Impact of five healthy building issues in the mental and physical health dimension across the EU and the Netherlands.

Table 9
Relationships between indicators, sub-indicators, and data collection attributes for five dimensions [171].

Dimension	Indicators/sub-indicators		Linked data [unit]	Frequency	Source	Last updated [year]
Improving mental and physical health	IAQ	Indoor air pollutants	Pollution rate [%]	Annual	EUROSTAT [175]	2020
			Premature deaths [number of deaths]	Annual	EUROSTAT [176]	2021
			Years life lost [number of years lost]	Annual	EUROSTAT [177]	2021
		Ventilation	N/A	N/A	N/A	N/A
		DMC	Population living in damp dwellings [%]	Annual	EUROSTAT [178]	2023
	Thermal comfort		Population living in a dwelling not comfortably cool during summer [%]	Once	EUROSTAT [179]	2012
			Inability to keep home adequately warm [%]	Annual	EUROSTAT [180]	2023
			Heating and cooling degree days [degree days]	Annual	EUROSTAT [181]	2023
			Average near-surface temperature [Celsius]	Annual	EEA [182]	2023
	Daylight, light, and visual comfort		Population considering dwelling too dark [%]	Annual	EUROSTAT [183]	2023
	Acoustics comfort		Population suffering from noise [%]	Annual	EUROSTAT [184]	2023
	Connectedness to nature		Urban tree cover/green infrastructure in Europe [%]	Once	EEA [185]	2018
			Distribution of population by degree of urbanization [%]	Annual	EUROSTAT [186]	2023
	Social connections		Frequency of contact with friends [%]	Twice	EUROSTAT [187]	2022
			Frequency of contact with family [%]	Twice	EUROSTAT [187]	2022
			Perceived social support [%]	Twice	EUROSTAT [188]	2019
	Design appeal		N/A	N/A	N/A	N/A
	Affordability		Housing cost overburden rate [%]	Annual	EUROSTAT [189]	2023
			Medical cost savings from repairs [GBP]	Once	Eurofound [25]	2016
Designed for human needs	Universal design		Overcrowding rate [%]	Annual	EUROSTAT [190]	2023
	Human-centered interaction		N/A	N/A	N/A	N/A
	Community design		N/A	N/A	N/A	N/A
	Intelligent building design		N/A	N/A	N/A	N/A
Sustainably built and managed	Energy and carbon emissions	Passive heating and cooling	N/A	N/A	N/A	N/A
		Energy-efficient systems and technologies	Renovation rate [%]	Once	EC [191]	2016
			Renewables share for heating and cooling [%]	Annual	EUROSTAT [192]	2022
		Operational energy	Final energy consumption for (households, commercial and public buildings) [thousand tons of oil]	Annual	EUROSTAT [193]	2021
			Energy Performance Certificates (EPC) share [%]	Annual	Internal BPIE database	2023
			CO_2 emissions for (households, commercial and public buildings) [tons]	Annual	ODYSSEE (not a public dataset)	2021
		Embodied energy	N/A	N/A	N/A	N/A
	Material and circularity		N/A	N/A	N/A	N/A
	Water		Worst seasonal water scarcity condition [water exploitation index plus (WEI +)	Once	EEA [194]	2019
	Management	High-quality construction throughout the life cycle of the building	Medical cost savings from repairs [GBP]	Once	Eurofound [25]	2016
		Construction and labor costs	Change in construction producer price [%]	Annual	EUROSTAT [195]	2023
Resilient and adaptive	Resilient to natural hazards	Earthquake-proof	N/A	N/A		N/A
		Severe weather conditions protection	Annual economic losses caused by weather – and climate-related extreme events [EUR]	Bi-annual	EEA [196]	2022
	Integrated resilient cooling and ventilation systems		N/A	N/A	N/A	N/A
	Blue and green infrastructure		Worst seasonal water scarcity condition [water exploitation index plus (WEI +)]	Once	EEA [194]	2019
			Urban tree cover/green infrastructure in Europe [%]	Once	EEA [185]	2018
			Distribution of population by degree of urbanization [%]	Annual	EUROSTAT [186]	2023
	Advanced smart and/or automated services		N/A	N/A	N/A	N/A
Empowering people	Skills and knowledge		Number of people in tertiary education for specific fields (like architecture, building, engineering)	Annual	EUROSTAT [197]	2022

(continued on next page)

Table 9 (*continued*)

Dimension	Indicators/sub-indicators	Linked data [unit]	Frequency	Source	Last updated [year]
	Effective communication	N/A	N/A	N/A	N/A
	Occupant behavior and control	N/A	N/A	N/A	N/A
	Information access and sharing	N/A	N/A	N/A	N/A

connectedness to nature, and IAQ. This example highlights the interrelatedness between the five dimensions but also presents an opportunity for the building sector to shift their thinking towards health. The framework presented in this paper can guide the building sector towards thinking about the multiple benefits of individual measures. However, the academic research behind the framework also highlights that while one measure might lead to multiple health benefits, each measure must be seen as part of the whole building. Energy efficiency measures can worsen air quality, especially if they are not well designed [67,68].

Furthermore, at the Member States or the EU levels, the empirical data matching exercise for indicators showed that data collection needs to improve. The lack of continuous and comprehensive data collection highlights significant data gaps at both the EU and member state levels. These gaps pose challenges in obtaining a holistic picture of healthy buildings using the presented framework, emphasizing the need for improved data collection and integration efforts to fully utilize the framework's potential. Additionally, challenges around matching indicators to existing datasets create issues for tracking individual indicators, as proxy datasets (such as outdoor air pollution and overcrowding rates) are not able to indicate the exact challenges for these indicators.

The developed framework can also be used to track progress on the health of the entire building stock of a city, region, country, or continent, but high-quality data are necessary. This application of the framework would allow a macro-level perspective that can guide involved stakeholders. Researchers can investigate areas where the health of buildings needs to be improved and suggest theoretical and practical ideas. The building sector can see where the shortfalls lie and address these through specific actions such as skills improvement of the workforce or changes in processes. Policymakers can use shortfalls to target their policies and funding streams.

As a summary, key recommendations from this paper are as follows:

- Ensure that documentation along the five dimensions of the Healthy Buildings Framework is integrated early into the design process of a building project.
- The assessment through the scoring procedure of each indicator and dimension allows to adjust building design, construction, or management during the initial stages to achieve its full health potential.
- Stakeholders such as researchers, designers, architects, construction companies, and building managers need to carefully map the interrelatedness of the individual measures carried out on a building project to ensure that the holistic nature of the framework is understood.
- Data collection at a macro level, such as countries and for the whole EU, needs to be aligned with the indicators of the Healthy Buildings Framework so that the progress of the health of building stocks can be tracked over time.
- Policymakers need to make use of the findings of this study and integrate the Healthy Buildings Framework into existing policies, as well as open funding streams to accelerate the realization of healthy buildings.

4.2. Strengths and limitations

First, this paper makes a significant contribution to the healthy buildings community by creating a holistic and coherent framework that integrates academic contributions with the practical efforts of the building and public sectors. This comprehensive approach ensures that the framework is well-rounded and applicable to a wide range of stakeholders, including those in academia, the construction sector, the health sector, and the public sector. Second, the paper introduces a novel definition of healthy buildings that synthesizes various individual aspects into a unified understanding. This integrated definition not only clarifies the concept of healthy buildings but also provides a clear and comprehensive guide for evaluating and improving building health across different contexts. By incorporating mental and physical health, human needs, sustainability, resilience, and empowerment, the framework covers all essential dimensions of healthy buildings. Third, the framework proposed in this paper is designed to be universally applicable and addresses all building types. This versatility ensures that the framework can be used by a diverse range of users, from researchers and practitioners in the built environment to policymakers and public health officials.

By considering the needs of people, the environment, and society as a whole, the framework provides a balanced approach that promotes both individual well-being and broader sustainability goals. This emphasis on people, sustainability, and adaptability makes the framework particularly relevant in addressing contemporary challenges in the building sector, including climate change and the increasing importance of health and well-being.

However, the paper has some limitations that should be acknowledged. First, the validation of the framework was conducted using only 12 case studies. While these case studies represent eight countries and various building typologies, such as residential, office, and school buildings, and provide valuable insights, a larger sample size is necessary to robustly test the framework. Expanding the validation to include more diverse building types, climates, and geographic regions will enhance the robustness of the framework and help identify any additional gaps or inconsistencies. Second, Dimension 2 – Designed for human needs, and Dimension 5 – Empowering people, present challenges in validation due to their reliance on qualitative indicators. These indicators often reflect implicit considerations by designers and architects, making them difficult to measure and validate objectively. Third, this paper establishes a universal framework for healthy buildings; it does not quantify specific performance targets or numerical benchmarks for the various indicators across different building types and uses. The framework is designed to be adaptable, but detailed performance criteria can still be developed separately, tailored to specific building contexts, functions, and occupant needs.

4.3. Implications on practice, policy, and future research

For future practices, the development of a Healthy Buildings Assessment Tool is proposed for decision-making in the building sector. This tool can be built using the method used to collect case study data across different European countries. It will support various stakeholders by providing strategies and guidance to determine if their designed or constructed buildings adhere to the Healthy Buildings Framework and cover all dimensions.

In addition to these practical implications, there is an invitation for academic research to further refine the framework. Continuous academic inquiry is crucial to enhance the framework's validity and reliability. Scholars are encouraged to engage in longitudinal studies, crossdisciplinary research, and comparative analyses to explore the framework's effectiveness and adaptability.

Future research should also focus on studying how best to apply the framework to different building segments, such as houses, schools, and offices, or investigating which building segments have strengths and room for improvement in terms of dimensions and indicators of the framework. It is possible that some segments are already strong in certain dimensions of the framework or that the concept of empowering people, for instance, may require different approaches between a residential home and a hospital. This line of inquiry will help to tailor the framework to the unique needs and conditions of different building types.

Moreover, identifying recommended ranges or levels for each indicator according to the building's use is critical for providing practitioners with concrete references during the design, construction, and management phases. For example, determining the optimal range of lighting in a house compared to a school can guide the creation of healthier and more functional spaces. Establishing these benchmarks will not only enhance the framework's practical utility but also offer clear guidelines that can be universally applied across various contexts.

Addressing data gaps and ensuring regular data updates are critical for the effective implementation of the Healthy Buildings Framework. Current analysis indicates that a significant portion of the required data is either unavailable or incomplete, which poses challenges in creating a comprehensive assessment of building health. To overcome these challenges, it is essential to establish systematic and consistent data collection processes at both the EU and Member State levels. This step involves not only gathering new data but also updating existing datasets regularly to reflect current conditions. Databases such as the BSO could be utilized [95]. By implementing robust data collection mechanisms and maintaining up-to-date datasets, stakeholders can ensure that the framework remains relevant and effective.

Additionally, improving data availability will facilitate better policy-making and support the development of targeted policy interventions to enhance the health of buildings across diverse contexts, especially with regard to the new EPBD. With the increasing push to renovate buildings, it is crucial to guide the relevant actors and policymakers about the correct focus on the health and well-being of citizens, along with energy efficiency and carbon emissions, which the developed framework will address. The holistic framework presents an excellent opportunity to develop and introduce specific requirements and measures through different policies at the EU and national levels.

CRediT authorship contribution statement

Essam Elnagar: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Caroline Düvier:** Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Zuhaib Batra:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Conceptualization. **Jens Christoffersen:** Writing – review & editing, Methodology, Investigation, Funding acquisition. **Corinne Mandin:** Writing – review & editing, Validation, Methodology, Conceptualization. **Marcel Schweiker:** Writing – review & editing, Resources, Investigation, Conceptualization. **Pawel Wargocki:** Writing – review & editing, Resources, Investigation, Conceptualization.

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.

Data availability

Most of the data utilized in this research are derived from publicly accessible sources, as detailed in the paper, with only a small portion consisting of non-public data.

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