Factors Influencing the Health-Promoting Impact of Buildings

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Abstract

Buildings have a significant impact on the health and well-being of their occupants through factors such as thermal comfort, humidity, air quality, access to natural light, acoustics, and radiation protection. The purpose of this study was to identify factors that contribute to healthy construction and to define the competencies needed in technical education to support the design and operation of health-promoting buildings. The study utilised expert brainstorming, an analysis of legal regulations in partner countries, a review of educational programmes, and a systematic review of the scientific literature. The research confirmed the positive impact of green buildings (e.g., LEED Certification) on occupant health. Gaps in technical education programmes were identified, particularly in the practical teaching of modern technologies and health-promoting design solutions. A competence matrix was developed, divided into educational levels, encompassing knowledge, skills, and social competencies related to the health-promoting aspects of buildings. Knowledge about healthy construction should include indoor environmental parameters, universal and ecological design, and conscious operating practices. The prepared competence matrix provides a foundation for further educational development and guides further research in this area.

Keywords: health-promoting construction; good practices; innovations in vocational education

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1. Introduction

1.1. Description of the Project—Purpose and Scope

Many factors influence human health, including the environment in which we live. Time spent outdoors varies depending on the season and weather, but the vast majority of people spend the vast majority of their time indoors. The Co4Health project explored how buildings impact human health.

The primary goal of the project was to identify factors that contribute to the health-promoting impact of buildings on their occupants and to improve the quality of educational offerings and their impact on the labour market and sustainable development by developing teaching materials that address the health-promoting aspects of construction, as well as solutions that modernise construction processes. Making knowledge transfer and competence acquisition more attractive can attract more young people to construction professions. Political support for educational institutions and units is essential to foster the potential of future construction workers. Another goal of the project was to inform teaching staff at the vocational and higher education levels about the need to expand educational offerings in the field of health-promoting construction. The purpose of the project was to prepare preliminary topics so that participants could assess the impact of the construction solutions adopted and select those that positively impacted the health of the occupants of the building. Initial activities focused on identifying the current state of knowledge and content within the curricula, as well as defining labour market requirements in terms of health-promoting construction competencies and ensuring high quality. This section analyses current legal regulations, regulations, and labour market requirements in the construction industry. Following this analysis, a proposed competence matrix was prepared for educational levels 3 (vocational schools) to 6 (engineering studies). Additionally, rules for documenting learning outcomes were developed, as well as the use of Europass and micro-credentials. The next step was to develop educational units on healthy construction for VET (Vocational Education and Training) and advanced training concepts for teachers at educational levels 3 and 4. Ready-made educational scenarios on healthy construction were prepared for various construction professions and were tested in schools of project partners. In addition, advanced training and a manual for teachers were developed to facilitate the expansion of their competencies and increase awareness of healthy construction. These were tested during joint educational activities and webinars conducted by project partners and external stakeholders.

The project was implemented through international cooperation between technical schools, companies, and research institutions. It aimed to exchange experiences and best practices, as well as to create innovative educational outcomes with the potential for broad application in the selected field of vocational education and training. The project leader was the Berlin Society for International Cooperation (Berlin, Germany). The partners were Poznan University of Technology (Poznan, Poland), Construction School Complex No. 1 (Poznan, Poland), Centre for Vocational Education and Development (Eupen, Belgium), Vocational Training Institution of the Construction Industry Berlin-Brandenburg (Berlin, Germany), Stichting CHAIN5 (Borculo, The Netherlands), Construction School Andrea Palladio (Vicenza, Italy), and Vocational Training Centre JEDU (Nivala, Finland). Thanks to the cooperation of schools from different countries in the project, the transparency and communication between vocational and higher education have improved.

The benefits of implementing the project for the university include access to innovative teaching materials and concepts from other European countries, the opportunity for direct contacts, and the acquisition of new partners for future larger projects, enabling support for the development of new concepts. The project also led to the development of a long-term cooperation strategy among vocational training, industry, and academia.

1.2. Research Area

The buildings in which people stay can be divided according to the following:

- Function: residential, office, service, industrial, healthcare, etc.,
- Time of construction: before the 20th century (traditional construction), 1900–1950 (partially industrialised construction), 1950–2000 (greater thermal insulation), and after 2000 (increased number of energy-efficient buildings and use of mechanical ventilation),
- Location: dense urban centre development, industrial areas, suburban areas, rural areas, etc.

Each type of building will have a different impact on the health of its occupants, but several thematic areas can be distinguished, as follows:

- Climate—temperature, humidity, and air quality,
- Comfort—acoustic, lighting, space, and ease of use,
- Safety—no harmful substances or radiation.

From a different perspective, the WHO has defined the concept of a sick building [1] as a set of health complaints that occur while inside and disappear after leaving the building. These complaints include the following:

- Eye,
- Nose and throat irritation,
- Mental fatigue,
- Headaches,
- Nausea,
- Dizziness and skin irritations.

It is possible to identify actions to counteract these influences.

Studies conducted in office buildings [2] analysed the impact of improving indoor environmental quality on health and productivity in people who moved from conventional buildings to green buildings certified according to the multi-criteria LEED (Leadership in Energy and Environmental Design) assessment, in which indoor air quality (IAQ) was assessed. Air quality is an important indicator and its good quality should be ensured. A reduction in absenteeism and work hours affected by asthma, respiratory allergies, depression, and stress was observed, as well as improved productivity. These preliminary findings indicate that green buildings can positively impact the health of occupants. The impact of improving air quality in buildings on health is achievable with a small financial investment [3,4], and the benefits for users are significant. Increasing air supply in green building ventilation systems requires optimising energy consumption, which means implementing energy-efficient systems and conscious operating practices [5]. These recommendations, examined in office buildings, can also be implemented in residential buildings, schools, and other areas. Currently promoted architectural, construction, and installation solutions that increase energy efficiency can result in low outdoor air permeability and reduced natural ventilation flow, thus increasing the concentration of pollutants in the environment [6]. Therefore, it is important to pay attention to the parameters of the ventilation system, especially in healthcare buildings. The components of the ventilation and air conditioning system, such as philtres, cooling coils, air intakes, and porous insulation in air ducts, can support the growth and spread of infection spores in some areas. However, sufficient sunlight and natural ventilation in other areas can disinfect pathogens [7]. The frequency of air exchange is not the only parameter that influences its purity; it is also important to reduce humidity (e.g., in ducts, humidifiers, coolers, etc.) [8,9], because spores use moist conditions to germinate and multiply. Recommendations to ensure a high-quality indoor environment include the following [10]:

- Increasing ventilation efficiency,
- Air purification by using philtres on devices that emit solid and gaseous particles,
- Periodic cleaning and replacement of philtres [11],
- Periodic replacement of internal linings, especially damp linings [12],
- Discharge of pollutants to the outside,
- Storing paints, adhesives, solvents, and pesticides in well-ventilated rooms,
- Degassing of pollutants from building materials before they are made available for use,
- Application of monitoring and control systems for internal environmental parameters [13].

In green buildings (LEED), access to courtyards, gardens, green terraces, public squares, and other types of open spaces is also an important aspect, as it contributes to a better perception of health [14]. It is recommended to plan several smaller buildings instead of a single large building, as this allows better access to the outdoor environment. A balance should be found in the design of interior spaces in terms of temperature, humidity, airflow, and light availability that is physically comfortable for people [9].

1.3. Regulatory Overview

A review of the requirements in force in the project partner countries showed that in all partner countries, there are legal regulations and standards regarding the required indoor air temperature, the indoor air humidity standards, and the interior orientation. Next in this regulation, to minimise health impacts, some recommendations on natural lighting and external views, air pollution, reduction in exposure to noise pollution, reduction in exposure to high- and low-frequency electromagnetic fields, reduction in indoor pollution levels, and use of materials with reduced emissions of pollutants are referred to. All partner countries strive to harmonise regulations, but due to the specificities of individual countries, certain discrepancies or omissions are still observed. In addition to the lack of certain regulations in the area of construction that promotes health, there is also a perceived lack of public awareness in this area.

In Poland, health-related issues are included in the Regulation on the technical conditions to be met by buildings and their location of 15 April 2022 [15]. Section VIII Hygiene and Health, § 309, specifies that a building should be designed and constructed of such materials and products and in such a way that it does not pose a threat to the hygiene and health of users or neighbours, in particular as a result of the release of toxic gases, the presence of harmful dust or gases in the air, dangerous radiation, pollution or poisoning of water or soil, improper removal of smoke, exhaust gases, impurities, and waste in solid or liquid form, the presence of moisture in building elements or on their surfaces, uncontrolled infiltration of outside air, the ingress of rodents into the interior, and limitation of sunlight and natural lighting. Meanwhile, issues related to ensuring accessibility for people with special needs are included in Article 7, amended by Article 44 point 1 of the Act of 19 July 2019 (Journal of Laws, item 1696) [16], which entered into force on 20 September 2019, in accordance with Art. 66 of the Act of 19 July 2019—Building Law [17], in the wording given by the Act of 19 July 2019 on ensuring accessibility, in particular taking into account the needs of people with special needs.

In strict connection with the above files, legal construction should observe provisions of the following standards: PN-EN 15643 Sustainability of construction works [18], PN-EN 15804 Environmental product declarations [19], PN-EN 16309 Assessment of social performance of buildings [20], and PN-EN 16627 Assessment of economic performance of buildings [21].

There are several laws and regulations regarding the impact of buildings on human health, both in terms of indoor air quality and building materials. Safety and Health to Encourage Improvements in the Safety and Health Protection of Workers at Work [22] establishes the values of indoor air quality parameters that are used to assess the health risk associated with the presence of pollutants in residential buildings, offices, and schools. These regulations require construction products, especially those that emit volatile organic compounds (VOCs), to meet certain health criteria. The Occupational Health and Safety Act [23] determines the impact of building materials on health and the environment. The working conditions act is implemented by a number of health and safety regulations with regard to certain risks in the workplace, such as hazardous substances and biological substances regulation. There is also regulation on preventive occupational medicine, on health and safety when using personal protective equipment at work, and on the protection of workers against risks relating to noise and vibrations. This regulation introduces an obligation for employers to take the necessary measures to prevent any harm to the health of employees exposed to noise or vibrations. Moreover, there is regulation on the protection of workers against risks relating to artificial optical radiation, electromagnetic fields, and the effects of electromagnetic fields [24].

In Italy also, the adoption of the Standard Building Regulations [25], as envisaged by the Agreement reached on 20 October 2016 between the State, Regions and ANCI (Official Journal no. 268 of 16 November 2016, ANCI—Association Italian Gmin), represents one of the pieces of the mosaic of simplification and unification actions in building matters promoted by the government. In this regulation, the building and interior orientation, natural lighting, and external view are described. Next, air pollution, reduction in exposure to noise pollution, reduction in exposure to high- and low-frequency electromagnetic fields, reduction in indoor pollution levels, and use of materials with reduced emissions of pollutants are regulated in order to minimise health impacts.

Finland has regulations on indoor air quality, building materials, and sustainable design. The Finnish National Building Code [26] specifies that a building must not pose a health risk due to air pollution, radiation, moisture, smoke, sewage, or improper waste treatment. The Finnish Indoor Air and Health Programme 2018–2028 [27] from the Finnish Institute for Health and Welfare aims to reduce the health risks associated with indoor air quality. It addresses factors such as mould, moisture, radon, and other factors that affect occupant health. The 2025 New Construction Act [28] emphasises sustainable construction and indoor environmental quality. It requires the use of low-emission materials and technologies that improve air quality.

In the Netherlands, there are regulations on the impact of buildings on human health, mainly contained in the Buildings Living Environment Decision [29] on the health of building users (moisture, ventilation, and air quality), construction safety, protection against noise and radiation, and building materials and their impact on the health of users.

Belgium also has regulations in place regarding the impact of buildings on human health, including indoor air quality, ventilation, and building materials. Its framework regarding indoor air quality [30] applies to all enclosed spaces accessible to the public. The act defines the reference levels for CO_2, requires a risk analysis and action plan, and introduces an air quality certification and labelling system.

The regulations mentioned above are dominated by regulations concerning air cleanliness; only Polish regulations take into account a wider range of factors affecting the health of building users.

Based on the review of the regulations, it was identified that a more detailed examination of the impact of buildings on health is needed and that specific factors should be identified.

Currently, a supporting programme in Europe is the Healthy Buildings Barometer, a guide for policymakers and stakeholders towards achieving healthier, more sustainable buildings. It offers a comprehensive framework based on 12 case studies from the EU to help policymakers and stakeholders move towards healthier, more sustainable buildings. The case studies were conducted in Denmark, France, Germany, the Netherlands, Slovakia, Spain, and Sweden. The barometer, now known as the Healthy Buildings Barometer (HBB) [31], extends its scope to all major building types, providing information on the health of buildings in Europe. It describes the current state of buildings in terms of indoor health and well-being. The HBB highlights the need for a more integrated approach to healthy buildings, so that all five dimensions of healthy buildings are considered simultaneously [31], as follows:

- Improvement in mental and physical health;
- Designing with human needs in mind;
- Sustainable construction and management;
- Resilience and adaptation;
- Supporting people.

In the EU Buildings report, Climate Tracker [32] presents progress in implementing decarbonisation of buildings and highlights the need to consider social aspects, including benefits related to the health and comfort of occupants and the quality of the indoor environment. There is a lack of coherent policy frameworks across countries and capacity building for professionals and decision-makers regarding the needs and requirements of healthy buildings.

2. Literature Review

A review of the literature presenting research on the impact of buildings on the health of occupants was carried out. The bases Semantic Scholar, Google Scholar, Elsevier, Springer, Scopus, and data Researchgate were used, using combination words. Keywords included the following: thermal comfort and user health, humidity comfort and health impact, clean air and impact on health, natural light and user health, acoustic comfort and user health, radiation protection and impact on user health, exposure to electromagnetic fields and impact on health, universal design and user health, eco-friendly buildings, and health benefits. The search process used combinations of keywords in English, including "thermal comfort", "humidity comfort", "building noise", "access to daylight", "air quality", "radioactive and electromagnetic radiation", "human health", and "sick building syndrome". To obtain the most current and reliable data, articles published in recent years in peer-reviewed scientific journals were considered. For medical studies, older publications were also considered. Publications were selected based on an analysis of titles, abstracts, and full texts, with an emphasis on empirical studies and systematic reviews that describe the impact of indoor environmental factors on human health and well-being.

2.1. The Impact of Thermal and Humidity Comfort in a Building on the Health of Its Users

The thermal conditions in buildings can affect the health of residents [31,32]. A study conducted among older adults in residential buildings in Australia showed that temperature fluctuations have a significant impact on well-being. Optimal indoor temperatures are between 15 °C and 28 °C. Outside of this range, cooling or heating devices were used, clothing was adjusted, and activity levels were changed. When temperatures were below 15 °C and above 28 °C, the windows were closed. There are no data on the type of ventilation in these buildings, but within the optimal temperature range, some windows were open. During periods of high temperatures, the occupants experienced fatigue, shortness of breath, insomnia, and skin irritation. In a study conducted in three types of Nigerian bungalows in a tropical climate, the temperatures varied between 25.5 °C and 31.09 °C during the dry season. Most of the respondents were dissatisfied with the thermal conditions. Symptoms included skin rash in 59.8% of people, heat exhaustion in 51.3%, heat rash in 42%, and heat cramps in 26.4%. It was noted that the type of construction materials used for the walls and roof, colour and type of paint, height of rooms, type and orientation of windows, and ventilation efficiency influenced thermal conditions [33].

A study of the relationship between the thermal environment in a building and human health was undertaken [34]. Temperature accounted for more than 76.68% of the parameters affecting human health, with the remaining factors being air movement (0.06%), humidity (0.05%), and others (0.12%). Occupants' symptoms were alleviated when temperatures remained between 20 and 23 °C in summer and below 22 or 23 °C in winter. These values differed for obese individuals and those with diabetes and cardiovascular disease. Humidity levels of 20–60% in summer and increasing humidity to 30–40% in winter can significantly reduce the incidence of symptoms.

The effects of temperature and humidity should be considered separately for the summer and winter periods. In winter data, an increase of 3 °C in average temperatures of

21.6 °C was associated with a significant increase in most symptoms of building disease. However, the same increase in summer temperatures resulted in reduced fatigue and difficulty concentrating [35]. Therefore, it can be recommended to reduce the intensity of air conditioning in summer, which will reduce energy demand.

The occupants of buildings prefer air conditioning and mechanical ventilation. Employees' subjectively reported health problems favoured natural ventilation over mechanical ventilation, as evidenced by the average absence from work due to health reasons [36]. Changes in employee performance are not only due to environmental factors, but also to psychological factors, including emotions and motivation. As negative emotions decrease or motivation increases in people, performance will also increase [37].

Maintaining indoor relative humidity at 40–60% can reduce symptoms of dryness, respiratory irritation, and sick building syndrome. Studies of office spaces with relative humidity in the range of 30–60%, with an optimal level around 45%, have shown a 25% reduction in stress, improved sleep quality for employees [38], and a reduction in allergic symptoms [39], leading to a reduced risk of infection [40]. A study of hospital workers also found that levels of 35–45% relative humidity reduced symptoms associated with dry air [41]. A study conducted in residential buildings across five climate zones in China found that higher relative humidity was less likely to cause mucosal or skin problems, but the benefits of high humidity were diminished when high CO_2 levels were present [42]. Excessive humidity in residential buildings, on the other hand, can increase the risk of mould, asthma, and atopic dermatitis [43]. These studies confirm that moderate indoor air humidity improves comfort and respiratory health in many building types.

2.2. The Impact of Clean Air in a Building on the Health of Its Users

Clean indoor air is associated with fewer symptoms of sick building syndrome and better work performance [5,11,44,45]. Volatile organic compounds and CO_2 should be limited. Employees in buildings with green building certification observe a 30% reduction in symptoms of sick building syndrome [46]. Studies have shown a reduction in headaches and respiratory symptoms after improving mechanical or natural ventilation, introducing new filters, or reducing the content of volatile organic compounds [47,48]. Interventions to increase ventilation efficiency, improve filtration, or implement green building practices can improve air quality and provide measurable health and productivity benefits in offices.

2.3. The Impact of Natural Light in Buildings on the Health of Their Users

People spend almost 90% of their time indoors. Access to natural light in buildings promotes better sleep, circadian balance, and mental well-being. Studies have shown an increase in sleep duration by 46 min and improved sleep quality in office workers who had access to natural light during work hours [49]. People who worked in windowless spaces had lower melatonin levels and higher cortisol levels, which translates into reduced sleep quality [50]. Studies conducted in residential buildings with windows equipped with adjustable blinds showed a 22 min earlier sleep onset time and improved sleep regularity [51]. Natural light improves mood, reduces stress, and improves cognitive performance by regulating circadian rhythms and promoting visual comfort [52]. Architectural factors such as window size, orientation, and the ability to adjust shading have a significant impact on sleep quality and well-being.

2.4. The Impact of Acoustic Comfort in a Building on the Health of Its Users

Poor acoustic conditions in buildings can have a negative impact on health. Research conducted in a hospital's cardiac intensive care unit showed that reduced reverberation time and improved speech intelligence increase work comfort, reduce fatigue, and stress among nurses, especially during the afternoon shift [53]. Similarly, in classrooms, higher noise levels or a larger number of students have been found to have a negative impact on the health and well-being of teachers (approximately 61%), and a negative impact of longer reverberation time (approximately 39%) has also been found, manifesting itself in increased fatigue, headaches, stress, and voice disorders in both teachers and children [54]. In offices and open-plan spaces, poor acoustics resulted in reduced productivity and job satisfaction [55–58], causing distraction. Factors related to building layout and acoustic insulation are important for occupant health. Materials can be made sound-absorbing to correct acoustic comfort [56,58,59].

2.5. E-Smog Comfort and the Impact of Radiation Protection in Buildings on the Health of Their Users

Studies conducted in residential buildings (Canada, Iran, and Spain) have shown that radon exposure in high-exposure regions is associated with a 10–20% population-based lung cancer rate, and integrated strategies combining shielding materials, ventilation, space design, and monitoring have a positive impact on occupant health [60]. Exposure to ionising radiation in buildings (in Nairobi) has been associated with the risk of diseases such as erythema, skin cancer, genetic mutations, and infertility [61]. The use of insulating materials in buildings is beneficial. Materials performance studies have shown that gypsum plasterboard transmits only 18% of electromagnetic radiation, compared with 96–97% for wood or glass, and that burnt clay bricks and lead sheets have radiation-shielding properties [62]. Material selection, ventilation, building layout, and insulation of installations influence radiation exposure levels.

Residential exposure to electromagnetic fields (EMFs) has been found to have variable correlations with sleep quality and cognitive function. There is no evidence of an effect on cardiovascular health. Studies measuring sleep duration and quality have shown that exposure—from power-frequency fields (e.g., 2 milligauss) to radio frequency fields (e.g., up to 4.1 mW/m^2)—may sometimes be associated with worsening sleep disturbances [63–68]. Cognitive assessments, based on neuropsychological tests and EEG analysis, reveal that greater exposure to 50/60 Hz frequencies is sometimes associated with poorer coding efficiency and increased psychiatric symptoms [69].

2.6. The Impact of Universal Design in a Building on the Health of Its Users

Universal building design solutions that take into account people's diverse needs and disabilities correlate with improved health for users from various social groups. Research in healthcare facilities indicates that intuitive room layouts are associated with improved usability, reduced stress, and improved well-being [70–72]. Transparency of communication in space and reliable accessibility measures that facilitate the removal of architectural barriers contribute to greater comfort and accelerate recovery [70,71]. Safety and comfort also improve satisfaction in workplaces and homes [73]. Ergonomics, better ventilation, and natural lighting improve well-being [70], and elements that encourage movement in office spaces reduce sedentary behaviour, thereby reducing musculoskeletal problems such as lower back pain, resulting in less absenteeism from work [2,74].

2.7. The Impact of Environmental Protection of a Building on the Health of Its Users

Green building solutions and environmental protection measures can have a positive impact on the health of occupants. A study examining the impact of moving to a sustainable office—one with natural ventilation, green walls, and cradle-to-cradle materials—observed a reduction in sick building syndrome symptoms and fewer sick days over two years, particularly among older workers [75]. Green-building-certified offices have been shown to generate 26% higher cognitive function scores and 30% fewer sick building symptoms compared to non-certified buildings [46]. Reductions in asthma, allergies, depression, stress, and absenteeism have been observed in LEED-certified environments [2]. In addition to incorporating green solutions into a building, it is also important to maintain its condition during use. Regular inspections, well-functioning ventilation, low-emitting materials, and thermal comfort are associated with better mental and respiratory health [76,77].

2.8. Quantitative Analysis

The optimal temperature and related air humidity in rooms for human comfort and health are the range of 22–24 °C with a relative humidity of 40–60% [36,42,78–82]. Temperatures outside this range may increase the risk of discomfort, decreased cognitive performance, and health problems such as respiratory symptoms or dry eye syndrome [36,42,81]. Humidity below 40% can cause dry skin, eyes, and respiratory tract, while humidity above 60% can promote the growth of mould and dust mites, increasing the risk of allergies and asthma [42,78,80,81]. Seasonal adjustments are important. In winter, lower temperatures of 20–22 °C with a slightly higher humidity of 30–40% are recommended [36,80,83], and in summer, 24–26 °C with humidity maintained within the range of 40–60% is recommended [36,83]. In high-humidity climates, thermal comfort can be achieved at higher temperatures up to 27–28 °C if humidity is controlled and airflow is increased, but relative humidity should still not exceed 60% for health [84–87]. The highest operating efficiency is achieved in the temperature range of 22–24 °C with 40–60% relative humidity [79,81]. Respiratory and skin health are also best protected within these ranges, minimising both dryness and microbial growth [42,80,81].

Based on the literature review, it can be concluded that more than 1 to 2 h of exposure to bright natural light during the day, especially in the morning hours, supports optimal sleep and the harmonisation of circadian rhythms in healthy adults [88–93]. Large population studies [94] show that each additional hour spent outdoors during the day is associated with better sleep quality, less insomnia, and improved mood.

The cleanliness of indoor air is determined primarily by the concentration of suspended particulate matter (PM), volatile organic compounds (VOCs), and carbon dioxide (CO_2) levels. Fine particulate matter ($PM_{2.5}$ and PM_{10}), primarily from cooking and heating, can cause respiratory and cardiovascular diseases. Lower concentrations are associated with better health outcomes [82,95–101]. Volatile organic compounds from the emissions of building materials, cleaning agents, and personal care products, as well as formaldehyde, can cause respiratory symptoms, asthma, and cancer [82,95–100,102]. Elevated CO_2 levels may impair cognitive function and comfort [82,99,103].

The limit on radioactive radiation in buildings is primarily intended to protect occupants from health hazards resulting from natural and artificial sources of building materials. Most international guidelines recommend that the annual effective dose of building materials should not exceed 1 millisievert (mSv) per year [104–108].

The limits of electromagnetic radiation in buildings are primarily determined by international safety guidelines, which establish maximum exposure levels to protect human health. Most countries follow standards set by organisations such as the International Commission on Non-Ionising Radiation Protection (ICNIRP) and Institute of Electrical and Electronics Engineers (IEEE), which establish frequency-dependent limits for both the general public and work facilities. Actual indoor exposure levels are typically well below these regulatory limits.

The electromagnetic radiation limit (according to ICNIRP) for a field of frequency 900 MHz is 28 V/m, and for 2 GHz, it is 61 V/m. The limits of power density are typically 4.5 to 10 W/m^2 depending on frequency [109,110].

To sum up the quantitative analysis based on the literature review, the optimal and limit values of individual parameters were determined and are presented in Figure 1.

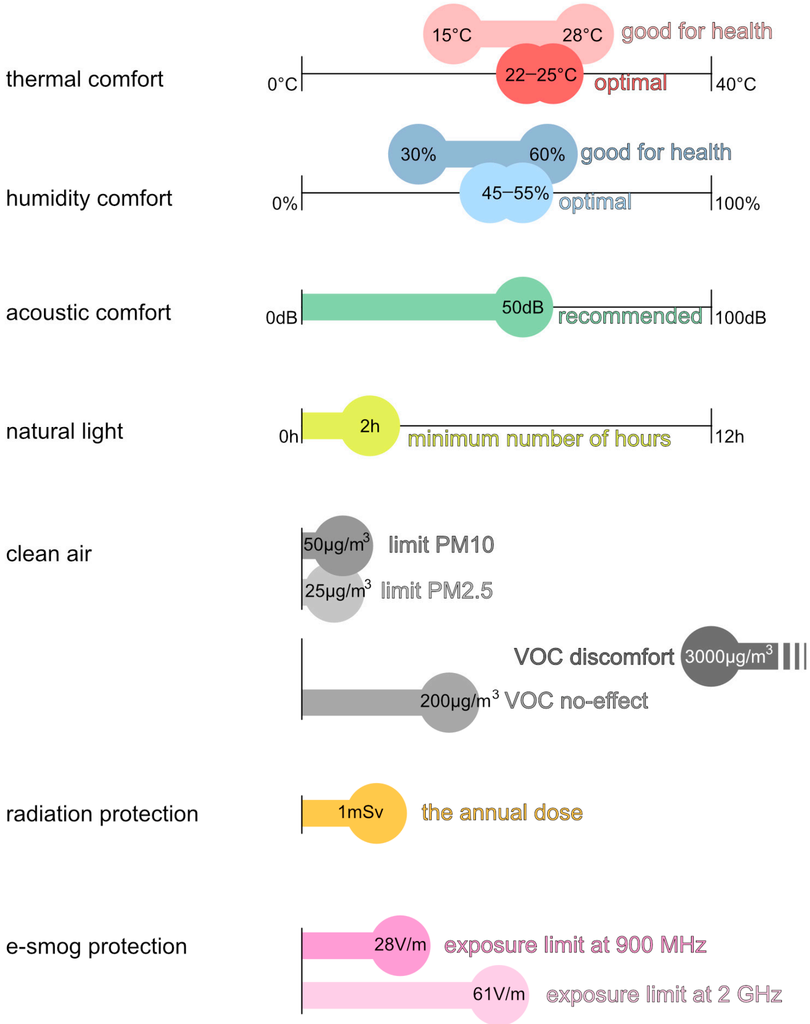

Figure 1. Optimal and limit values of individual parameters inside the building.

2.9. Case Studies

A case study conducted in an office building confirms that improving the quality of the indoor environment impacts occupants' health and work efficiency. Research conducted by Kanika and Felguerias [57,111] showed that the implementation of intelligent ventilation control systems, e.g., those based on Internet of Things (IoT) technology, can lead to significant improvements in both air quality and energy efficiency in buildings. These systems use a network of sensors that monitor indoor environmental parameters in real time, including carbon dioxide (CO_2) concentration, air humidity and temperature, and the level of suspended particles ($PM_{2.5}$ and PM_{10}). Automatic regulation of ventilation intensity and filtration based on these data allowed for a reduction in CO_2 and particulate matter emissions, while simultaneously reducing energy consumption thanks to the optimisation of HVAC systems (HVAC—Heating, Ventilation, Air Conditioning). As a result, employee health benefits were observed, as sick leave decreased. The employees reported improved concentration and reduced fatigue and headaches. These effects confirm the importance of indoor air quality as a factor in human well-being. Opinions regarding the satisfaction and subjective feelings of the building's occupants, where the indoor climate is controlled using IoT, are important [57]. This system is acceptable if the majority of users do not express dissatisfaction.

The open-source software tool BuildingGym v0.1.0 (based on Python 3.11, available on GitHub: https://github.com/BuildingGym/BuildingGym, accessed on 5 September 2025) can be used to optimise energy efficiency and indoor environmental parameters, for example, by adjusting the timing and power of air conditioning in an office building depending on weather conditions and room occupancy, or controlling building ventilation to maintain good air quality with minimal energy consumption. The tool is based on building models created in EnergyPlus (a simulation programme developed by the U.S. Department of Energy to model energy consumption, temperature, air quality, and thermal comfort in buildings) and their integration with reinforcement learning (RL) algorithms to control, among other things, heating, ventilation, and air conditioning. BuildingGym, a reinforcement learning (RL) tool for energy management in buildings, can be used in several ways [112], as follows:

- To optimise the control of HVAC systems—adaptive management of temperature, ventilation, and lighting in office, residential, and hotel buildings by dynamically adapting to load and changing environmental conditions,
- By supporting demand response strategies, enabling control systems to learn to shift load,
- To optimise energy storage based on grid signals to reduce peak costs and emissions,
- To coordinate complex building energy systems, such as microgrids that combine photovoltaics, electric vehicle charging, and storage,
- To increase self-consumption and minimise operating costs.

A literature review analysing studies related to predicting the presence and behaviour of users (e.g., opening windows) using machine learning models in smart buildings [113] showed that predicting the presence of people can significantly support HVAC and ventilation systems—including reducing energy consumption by better matching ventilation operation to actual room usage. Another review of the literature [114] showed that data quality (IoT sensors, internal building data, and logistical data) has a significant impact on the effectiveness of models, but a hybrid approach, i.e., combining different algorithms and different types of data, can improve the accuracy and stability of predictions. Occupancy prediction algorithms based on the Transformer model [115] can significantly improve the efficiency of building control systems. Accurate forecasting of the number of people allows one to adjust the operation of ventilation and HVAC systems to actual demand. The authors indicate that the Transformer model achieves better results than classic ML methods (decision trees, RF, LSTM, and XGBoost). Systems equipped with such a model can operate more dynamically—for example, temporarily increasing ventilation when a peak occupancy is predicted and decreasing it when the number of people decreases, which translates into lower energy consumption and better compliance with actual demand.

Similar conclusions were drawn from a case study in a high-rise residential building in Dubai [116], where an integrated ventilation system was implemented. Particular emphasis was placed on improving air exchange in rooms with a higher risk of contamination, such as kitchens and bathrooms. After upgrading the ventilation system, it was observed that formaldehyde and volatile organic compound (VOC) concentrations were reduced by 83 to 92%, which translated into a noticeable improvement in air quality and reduced occupant exposure to respiratory irritants.

Similar trends were observed in a case study of an educational building. Research conducted in schools [117,118] showed that during the winter period, when ventilation of rooms is reduced, indoor air quality significantly deteriorates, resulting in exceeding the recommended limits for CO_2 concentration in the air and the amount of suspended particulate matter. The introduction of automatic ventilation systems with heat recovery allowed good air parameters to be maintained, ensuring thermal comfort for students and teachers.

2.10. Research Gap and Novelty

Much of the available research on the impact of the environment on human health comes primarily from the medical field. However, it is necessary to integrate it with knowledge in the construction field to fully identify the factors that determine the health-promoting impact of buildings on occupants. This need highlights a significant research gap, including the lack of sufficient interdisciplinary analyses that combine medicine, architecture, and environmental engineering. Previous studies have separately analysed the design of health-promoting buildings and education in this area. However, few have explored how knowledge about building design that promotes health can be incorporated into an educational framework for construction professionals. This work addresses this gap by attempting to link the results of medical research with design and construction practice, demonstrating how indoor environmental parameters impact the health and well-being of occupants. Only such an approach enables the creation of spaces that truly support human health. Therefore, all actions that aim to optimise the thermal, acoustic, lighting, humidity, and air quality conditions should be considered a key element of the building design and construction process. These issues should also find a permanent place in the curricula of technical schools and universities educating in the fields of architecture, construction, and environmental engineering, so that future specialists are aware of their importance and are able to implement solutions that promote human health.

3. Materials and Methods

The planned research, aimed at developing a competence matrix, was divided into stages. The first stage involved an analysis of the regulations, standards, and guidelines in place in the countries where the project partners originated. Current requirements were identified with respect to building-related parameters that can affect occupant health, such as the quality and comfort of the indoor environment. The results of the analyses revealed similarities and gaps in the approaches of individual countries to health issues in architecture and construction. The outcome of this stage served as the starting point for the next step, a review of the scientific literature.

A systematic literature review was conducted to gather current research findings on the impact of indoor environmental factors (including thermal, acoustic, and light comfort, air quality, and radiation) on human health. This stage provided theoretical knowledge. The results were used to select topics for analysis during workshops and brainstorming sessions.

The next step involved workshops and brainstorming sessions with project partners from various European countries and teachers in various fields—architecture, construction, and environmental engineering. The goal was to synthesise the findings from the previous stages and identify areas for further exploration.

In the next stage, the curricula of technical schools and universities in the partner countries were analysed to find content already present in the curricula and identify areas that needed supplementation.

The data obtained in all the preceding stages were used in the process of developing a competence matrix in terms of knowledge, skills, and awareness of the need for health-promoting building design at the stages of design, construction, and operation.

The research process flow chart is presented in Figure 2. The next steps were based on the results from the previous stage. The purpose of the process was to develop a competence matrix regarding health-promoting factors in buildings.

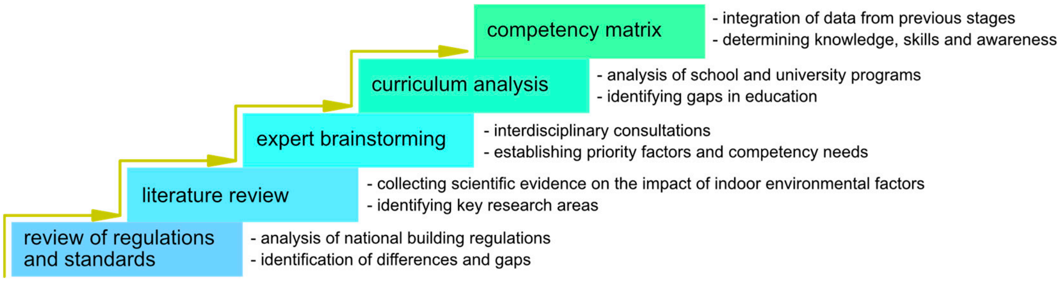

Figure 2. Diagram illustrating the research process.

3.1. Expert Brainstorming

During meetings (both in-person and online) among project partners, brainstorming sessions focused on the competencies needed to promote health-promoting construction education at various levels of education. The following areas were identified:

- Thermal comfort—energy-saving construction/energy-saving building technology;
- Moisture comfort—avoidance of mould problems/moisture in building components and on surfaces;
- Improving air quality/by avoiding harmful dusts and gases and toxic fumes;
- Use of natural light and avoidance of overheating through shading;
- Acoustics—protection against noise and vibration/noise protection, including infrasound;
- Protection from radiation/use of materials with as little radioactivity as possible/protection against too high radon exposure;
- E-smog—minimising electromagnetic fields and radio waves in buildings;
- Safeguarding the quality of drinking water;
- Environmental protection—green buildings/use of ecological and sustainable building products with the best possible ecological balance sheet.

During one of the in-person meetings, participants were divided into two teams. The task was to jointly formulate new competencies in the areas of knowledge, skills, responsibility, and autonomy that are or will be needed in the future for the aforementioned areas. The results served as the starting point for preparing a preliminary competence matrix.

3.2. Overview of the Curriculum

For the project, each partner reviewed the learning outcomes for selected construction-related professions at the education level (3 to 6) for their own country. For example, in Poland, the following professions were analysed:

- Construction technician (profession code: 311204), taking into account the following qualifications distinguished in the profession: BUD.12: Carrying out bricklaying and plastering works and BUD.14: Organisation and control of construction works and preparation of cost estimates; this corresponds to level IV of the Polish Qualifications Framework, which corresponds to level 4 of the European Qualifications Framework (EQF—European Qualifications Framework);
- Civil Engineer—a study programme for the field of Civil Engineering, conducted at the Poznan University of Technology; the graduate obtains the ISCED classification: 0732 construction and civil engineering (ISCED—International Standard Classification of Education);
- Sustainable Construction Engineer—a study programme for the field of Sustainable Construction, conducted at the Poznan University of Technology in English; the graduate obtains the ISCED classification: 0732 construction and civil engineering.

The following professions were analysed in other countries:

- At level 3 (studies at a first-degree vocational school):
    - Construction worker,
    - Fitter of construction and finishing works in construction,
    - Construction worker.
- At level 4 (studies in a vocational school or technical school):
    - Construction technician,
    - Finishing technician,
    - Bricklayer,
    - Roofer,
    - Carpenter,
    - Drywall installer,
    - Plasterer,
    - Painter,
    - Screed layer,
    - Construction carpenter,
    - Construction technician,
    - Water engineering technician,
    - Hydraulic engineering technician,
    - Landscape architecture technician,
    - Facility manager,
    - Carpenter, joiner,
    - Road construction technician,
    - Construction production worker.
- At level 5 (higher secondary education, such schools do not exist in all EU countries): the profession of a technician specialising in acoustics (Italy),
- At level 6 (first-cycle studies in universities and higher vocational schools):
    - Construction engineer,
    - Master carpenter,
    - Architect,
    - Heating engineer,
    - Investor's supervision inspector.

4. Results

4.1. From Brainstorming

During the brainstorming session, nine thematic areas were analysed, but the participants filled in the matrices only on the following topics:

- Thermal comfort,
- Moisture comfort,
- Quality of drinking water,
- Environmental protection—green buildings.

The remaining topics remained unaddressed. This was, in part, due to the presence of these topics in current regulations and curricula, but also to the narrow specialisations of teachers who did not consider themselves experts in their respective fields.

The proposals entered the most frequently were knowledge competencies (21), followed by skills (10), and the least of all responsibility and autonomy (5).

4.2. From the Curriculum

The analyses of current curricula reveal that many issues related to the health of users and construction workers are addressed. These can be divided into the following:

- Competences directly related to healthy construction,
- Competences indirectly supporting (e.g., health and safety in the workplace, ergonomics, and ecology).

For example, for the professions of construction technician and engineer, the curricula include, among others, competences related to the following:

- Level 4:
    - Choosing solutions with low emissions of harmful substances,
    - Organising safe working conditions, reducing hazards caused by noise, vibrations, etc.,
    - Taking into account sustainable transport and its impact on minimising dust and moisture on construction sites and in warehouses,
- Level 6:
    - Designing energy-efficient and user-friendly facilities,
    - Control of humidity and air quality, ensuring a healthy microclimate in buildings,
    - Minimising the impact of construction on the health of residents,
    - Selection of materials and solutions supporting a healthy living environment,
    - Monitoring the technical condition of facilities in terms of user safety,
    - Spatial planning that supports a healthy living environment,

4.3. Matrix

Based on the results of the literature search, the comparison of the regulations in force in the countries of the project partners, and brainstorming, a matrix of proposed competences was prepared, which can be added to school and university curricula for professions related to architecture, construction, and environmental engineering.

The matrix is divided into the following two parts: for secondary technical schools (levels 3 and 4) and for universities (levels 5 and 6) (Supplementary Materials). Each item specifies the area it covers. Table 1 provides the number of proposals for each area. The number of competencies defined for each topic area does not reflect its importance. Areas with fewer competencies can become the subject of further research to determine how a given aspect impacts human health.

Table 1. Number of competence proposals for individual areas.

Area Thematic	Teaching Levels 3 and 4			Teaching Levels 5 and 6		
	Knowledge	**Skills**	**Responsibility and Autonomy**	**Knowledge**	**Skills**	**Responsibility and Autonomy**
Thermal comfort	6	5	0	13	8	0
Humidity comfort	7	5	0	6	5	0
Clean air	2	2	1	4	0	0
Natural light	0	0	0	3	3	0
Acoustic comfort	1	3	0	4	2	0
Radiation protection	3	1	1	4	1	1
E-smog protection	0	0	0	1	1	0
Universal design	1	2	1	2	1	1
Environmental protection	7	2	3	8	0	3

In connection with the proposed competencies, several new professions have been proposed that could complement industries related to architecture, construction, and environmental engineering.

- Facility manager,
- Audit activity,
- Energy advisor,
- Construction and insulation technician (Italy),
- Construction technician in the field of programming and automation (e.g., roof joinery, gates, and windows),
- Representative for prevention and well-being at work,
- Heating engineer and qualified companies (Italy),
- Construction technician in the scope of a wider adaptation of facilities for elderly people.

5. Discussion

Most studies cited in the literature are based on subjective declarations (surveys and self-assessment of symptoms), which limits the possibility of inferring causality. It is unclear whether the observed symptoms are directly due to microclimate parameters or other related factors (e.g., smoking). In some cases, improved well-being may result not from actual environmental changes, but from a psychological effect (the so-called green label effect), i.e., the subjective feeling of staying in a "healthy" and "modern" building. Certificates such as LEED or BREEAM (BREEAM—Building Research Establishment Environmental Assessment Methods (Amendments) encompass a wide range of criteria—from energy efficiency to location—making it difficult to clearly identify which of the solutions used (e.g., ventilation, materials, and vegetation) are crucial for occupant health. The vast majority of studies cited concern office buildings, which limits the generalisability of the results to other types of buildings, such as schools, hospitals, and residential buildings.

Furthermore, studies cover different types of buildings, construction materials, and climate zones, as well as population groups (elderly people, sick people, and children), making it difficult to compare results and assess their reliability. The results of different studies recommend different optimal thresholds. These discrepancies may be due to seasonality and the characteristics of the study population, making it difficult to formulate clear recommendations. Standardised research protocols are needed.

Research on the effects of electromagnetic fields is highly inconsistent. Some studies show a link between exposure and sleep disturbances or reduced cognitive performance, while others do not confirm such effects.

Although the studies conducted provide valuable insight into the development of healthy building competencies, several limitations should be noted to properly interpret the results and guide future research. The first limitation comes from the fact that the study was based on a limited number of brainstorming participants and pilot lessons, which limits the generalisability of the results. Although discussions allowed the elicitation of important perspectives from teachers from different countries, the sample size does not reflect the full diversity of educational systems and cultural contexts. Therefore, the results should be interpreted as exploratory rather than universal. The second limitation comes from the way the pilot lessons were conducted. They were intended to test the proposed competence framework. However, they were conducted in selected EU countries and educational institutions, and, therefore, reflect specific curricular structures, learning cultures, and resources. These contextual factors may have influenced the implementation and assessment of competencies. Wider implementation of pilot lessons in other countries, at different levels of education, and in different types of programmes would be necessary to confirm the adaptability and robustness of the framework. It should be emphasised that the geographical scope of the study was limited to selected countries, mainly European. Building design education and health-related competencies can vary significantly between regions characterised by different climates, building regulations, and cultural expectations of comfort. Therefore, future research should strive to broaden the empirical base by including a broader range of international case studies and testing the framework in diverse climatic and institutional contexts. Despite these limitations, the scope of this study remains significant. It represents one of the first attempts to translate the evidence on healthy built environments into a structured competence framework that can be used in education, training, and policy. The identified limitations do not detract from the value of the study, but suggest promising directions for further development, including comparative research, large-scale validation, and long-term monitoring of learning outcomes. Considering these areas will enable the refinement of the competence model and enhance its potential to shape a healthier and more sustainable built environment.

The largest number of competence proposals were proposed in the following areas: thermal and humidity comfort and environmental protection. Maintaining optimal temperature and humidity levels in spaces occupied by people has the greatest impact on their health. Current multi-criteria analyses evaluate many aspects of a building, not only to reduce its negative impact on the environment, but also to promote the creation of a healthy environment for people inside. It is worth using the guidelines developed by certifications in the building design stage, but contractors should also be aware of the parameters of building materials and installation systems that are essential for ensuring a healthy indoor environment.

In the areas of acoustic comfort, clean air, and radiation protection, fewer competencies to complement the matrix were proposed, but these factors also impact human health. Silence affects not only comfort while indoors, but also mental health. Clean air is particularly important for people with allergies. Protection from natural radiation from the ground and building materials is important for cancer prevention. Universal design, which means adapting a building to the needs of people with various disabilities, should be the standard in buildings due to an ageing society and equal rights for all.

The fewest competencies were proposed for natural areas, as well as light and e-smog protection. Access to natural light positively affects sleep quality, which is reflected in health. People currently spend most of their day indoors, so buildings should be designed to optimise sunlight exposure. Excess sunlight causes interiors to overheat, so designs should incorporate shading systems that allow users to adjust the amount of light to suit their needs. E-smog can be caused by proximity to power lines and also by antennas emitting electromagnetic fields. This area requires additional research on its impact on human health, but some findings suggest negative impacts on sleep quality and mental health.

Tables 2–10 summarise the most important findings, divided into research areas. These findings were used to formulate proposals to supplement competence matrices in the areas of knowledge, skills, responsibility, and autonomy for secondary and higher education institutions in the architecture, construction, and installation professions.

Table 2. Comparison of the most important conclusions of the literature review and the most important selected competences included in the matrix for thermal area comfort.

The Most Important Conclusions from the Literature Search	The Most Important Competencies Proposed in the Matrix (Level of Education Is Given in Brackets)
Impact of Temperature on Health: Temperatures above 28 °C or below 15 °C in residential buildings can cause fatigue, shortness of breath, insomnia, and skin irritation. Optimal Workplace Conditions: In offices, maintaining temperatures between 21.6 °C and 24.8 °C is recommended, which reduces respiratory, eye, and skin symptoms. Temperature Control and Health: Greater user control over thermal settings improves self-perceived health, while deviations from optimal conditions can negatively impact concentration, productivity, and mood.	Knowledge (3, 4) - Knowledge of building materials and their proper use in the project in terms of **thermal insulation** - Knows legal regulations and technical solutions related to thermal insulation in buildings - Knows the principles of building **energy-efficient buildings** Skills (3, 4) - Is able to calculate heat transfer coefficients - Adapts to the selection of materials and technologies that ensure adequate thermal insulation - Can install materials for thermal insulation Knowledge (5, 6) - Knows the physical properties of various thermal insulation materials - Has extensive and specialised knowledge of the detailed **requirements for energy-neutral buildings** - Knowledge about the possibilities of **using solar energy** to heat building interiors Skills (5, 6) - Adapts to the use of specialised software in **thermal analyses** of a building - Can design an energy-efficient building - Is able to integrate **energy-neutral solutions** with digital building models

Table 3. Comparison of the most important conclusions of the literature review and the most important selected competences included in the matrix for humidity area comfort.

The Most Important Conclusions from the Literature Search	The Most Important Competencies Proposed in the Matrix (Level of Education Is Given in Brackets)
Optimal Humidity: Maintaining the relative humidity between 40 and 60% reduces symptoms of dryness, respiratory irritation, and sick building syndrome. Health Benefits: Humidity levels between 30 and 60% (optimally around 45%) in offices reduce stress by 25% and improve sleep quality, and in geriatric wards, reduce symptoms associated with dry air. Hazards of Excess Humidity: Excess humidity can increase the risk of mould growth, asthma, and atopic dermatitis, with high risk factors for these conditions.	Knowledge (3, 4) - Knowledge about the dangers of mould in buildings - Knowledge of building materials and their proper use in the project in terms of moisture insulation - Knows waterproofing materials Skills (3, 4) - Is able to properly install waterproofing, vapour barrier, and vapour permeable foils - Adapts to the selection of materials and technologies for moisture insulation - Can perform professional sealing of a building partition Knowledge (5, 6) - Has detailed knowledge of the building's tightness - Has detailed knowledge of building physics in the field of protection against moisture in buildings - Has a detailed knowledge of the impact of humidity on thermal comfort Skills (5, 6) - Is able to properly design connections of walls, ceilings, and roofs in order to avoid thermal bridges - Is able to determine the cause of moisture in building elements - Is able to calculate **water vapour condensation** in building partitions

Table 4. Comparison of the most important conclusions of the literature review and the most important selected competences included in the matrix for the clean area air.

The Most Important Conclusions from the Literature Search	The Most Important Competencies Proposed in the Matrix (Level of Education Is Given in Brackets)
Improved air quality: Clean indoor air reduces symptoms of sick building syndrome and improves work productivity. Ventilation benefits: Increasing ventilation by 20 cfm per person increases cognitive performance by 18%, and doubling ventilation improves productivity by 1.7%. Green certifications and productivity: In green-certified environments, symptoms of sick building syndrome are reduced by 30%, and additional studies indicate a 6–11% increase in productivity and a 6.5% increase in typing speed.	Knowledge (3, 4) - Knowledge about the release of **harmful substances** from building materials - Knows the basics of human chemistry and physiology Skills (3, 4) - Knows how to clean and maintain air conditioning systems - Knows how to properly use tools and handle highly volatile substances during construction Responsibility and Autonomy (3, 4) - Understands the importance of maintaining **proper ventilation** and air quality within a building to maintain a healthy indoor environment Knowledge (5, 6) - Knows the regulations regarding **air cleanliness** standards in buildings - Has knowledge about environmental **toxins** in the human body

Table 5. Comparison of the most important conclusions of the literature review and the most important selected competences included in the matrix for natural area light.

The Most Important Conclusions from the Literature Search	The Most Important Competencies Proposed in the Matrix (Level of Education Is Given in Brackets)
Better sleep and circadian rhythm: Access to natural light in offices improves sleep quality, increasing sleep duration by 46 min, and increasing sleep efficiency. In homes, dynamic glazing accelerates sleep onset by 22 min and improves sleep regularity. Health benefits: Increased access to daylight lowers cortisol levels, increases melatonin levels at night, improves mood, and reduces depression. Architectural factors: Window size, orientation, and advanced glazing types enhance these benefits.	Knowledge (5, 6) - General knowledge of **the impact of sunlight** on the human body - Knows the regulations regarding the required time of **natural lighting** in rooms Skills (5, 6) - Knows how to select sun protection systems - Is able to calculate the sunlight exposure in rooms

Table 6. Comparison of the most important conclusions of the literature review and the most important selected competences included in the matrix for acoustic area comfort.

The Most Important Conclusions from the Literature Search	The Most Important Competencies Proposed in the Matrix (Level of Education Is Given in Brackets)
Negative acoustic effects: Poor acoustic conditions in buildings are associated with fatigue, headaches, stress, and voice disorders in teachers and children, as well as reduced productivity and comfort in offices. Improved acoustic conditions: Improved reverberation time and speech intelligibility in hospitals reduce fatigue and stress among nurses. In offices, improved acoustics are associated with fewer physical and psychological symptoms and greater satisfaction. Architectural factors: High population density and inadequate sound insulation worsen conditions, while sound-absorbing materials and appropriate spatial planning improve productivity in some areas.	Knowledge (3, 4) - Has general knowledge about the impact of sounds and infrasound on health Skills (3, 4) - Is able to properly install window joinery for **acoustic protection** - Is able to install **anti-vibration protection** Knowledge (5, 6) - Knows the principles of acoustic insulation and vibration isolation - Knows the principles of building design buildings with regard to protection against noise and vibrations Skills (5, 6) - Can measure and calculate **interior acoustics** - Adapts to the selection of appropriate materials and technologies for acoustic insulation and anti-vibration protection

Table 7. Comparison of the most important conclusions of the literature review and the most important selected competences included in the matrix for radiation area protection.

The Most Important Conclusions from the Literature Search	The Most Important Competencies Proposed in the Matrix (Level of Education Is Given in Brackets)
Radiation Protection: Protective measures in buildings reduce exposure to radon, ionising radiation, and electromagnetic fields, while improved ventilation and insulation reduce radon penetration. Material Properties: Gypsum plasterboard transmits only 18% of electromagnetic radiation, while wood and glass transmit 96–97%. Ceramic brick, lead sheets, and barium plaster have promising protective properties. Health Impact: High radon exposure is associated with a 10–20% rate of lung cancer in the population. Integrated protection strategies, such as material selection, ventilation, space design, and monitoring, theoretically improve the health risk profile.	Knowledge (3, 4) - Knows the types of soil with higher **radon content** - Knows which building materials have the highest content of radioactive elements Skills (3, 4) - Can perform tight insulation of foundations and floors on the ground using roofing felt or foil—also to **protect against radioactive radiation** Responsibility and Autonomy (3, 4) - Understands the need for radiation protection Knowledge (5, 6) - Knows the permissible values of **the annual equivalent radon concentration** in rooms of a building intended for permanent human stay - Knows **the principles of ventilation** in the building Skills (5, 6) - Adapts to the selection of building **materials with low radioactivity** Responsibility and Autonomy (5, 6) - Understands the need for protection against radiation

Table 8. Comparison of the most important conclusions of the literature review and the most important selected competences included in the matrix for the e-smog protection area.

The Most Important Conclusions from the Literature Search	The Most Important Competencies Proposed in the Matrix (Level of Education Is Given in Brackets)
Effects on sleep: Exposure to electromagnetic fields can sometimes cause sleep disturbances, such as difficulty falling asleep and staying asleep, although not all studies support these effects. Cognitive function: Higher levels of exposure to electromagnetic fields (50/60 Hz) can be associated with poorer performance on neuropsychological tests and increased psychiatric symptoms, although no significant effects on speed and accuracy of perception at high frequencies were found. Lack of cardiovascular health data: None of the reviewed studies examined the effects of exposure to electromagnetic fields on cardiovascular health in residential settings.	Knowledge (5, 6) - Knows the regulations governing the location of buildings with rooms for people to stay in order to protect against **the effects of electromagnetic fields** Skills (5, 6) - Can design the partitions of a Faraday Cage

Table 9. Comparison of the most important conclusions of the literature review and the most important selected competences included in the matrix for universal area design.

The Most Important Conclusions from the Literature Search	The Most Important Competencies Proposed in the Matrix (Level of Education Is Given in Brackets)
Improving health in diverse environments: Universal design solutions in buildings, such as intuitive layouts, improved ventilation, natural lighting, and user control, improve usability, reduce stress, and improve well-being. Impact on healthcare: In hospitals, spatial clarity and reliable accessibility measures increase comfort and can influence the healing process. Benefits in offices: Active design strategies in offices reduce sedentary behaviour, musculoskeletal complaints (e.g., lower back pain), and absenteeism.	Knowledge (3, 4) - Has general knowledge of the principles of universal design Skills (3, 4) - Is able to install elements of **textured pavement markings** - Can install **stair platforms** for disabled people Responsibility and Autonomy (3, 4) - Understands the diversity of needs of different people in the aspect of universal design Knowledge (5, 6) - Knows the principles of universal design Skills (5, 6) - Is able to design buildings with eliminated **architectural obstacles** Responsibility and Autonomy (5, 6) - Understands the diversity of needs of different people in the light of universal design

Table 10. Comparison of the most important conclusions of the literature review and the most important selected competences included in the matrix for environmental area protection.

The Most Important Conclusions from the Literature Search	The Most Important Competencies Proposed in the Matrix (Level of Education Is Given in Brackets)
Health benefits of green buildings: Moving to a sustainable office with natural ventilation, green walls, and cradle-to-cradle materials reduces symptoms of sick building syndrome and sick leave, especially among older workers. Improved cognitive function: Certified green offices increase cognitive function scores by 26% and reduce symptoms of SBS by 30% compared to non-certified buildings. Air quality and health: Higher ventilation rates and lower levels of volatile organic compounds improve cognitive function and respiratory health, while measures energy efficiency without adequate ventilation can worsen indoor air quality.	Knowledge (3, 4) - Has knowledge about the impact of building materials on the environment - Knows what materials can be reused - Has general knowledge of what **sustainable construction** is Skills (3, 4) - Adapts to apply/use, explain, recognise, and handle building materials - Can recognise conditions installation Responsibility and Autonomy (3, 4) - Feels responsible for protecting the environment - Understands **the importance of ecology** - Understands the need to choose building materials that are friendly to people and the environment Knowledge (5, 6) - Has detailed knowledge of what sustainable construction is - Knows the basic criteria for the **multi-criteria certifications** BREEAM, LEED, FITWEL, WELL, and DGNB - Has general knowledge about carbon footprint Responsibility and Autonomy (5, 6) - Feels responsible for environmental protection - Understands the importance of ecology - Understands the need to choose **human/environmentally friendly building materials**

It is important to note that this research fills a critical gap identified in the cited literature. The most important element is the lack of a structured competence model that links building performance parameters with occupant health and comfort. Although numerous studies have demonstrated the importance of indoor environmental quality for health [12,13,46], these findings have rarely been translated into educational models that support vocational training. The competence matrix proposed here bridges this divide by transforming empirical observations into educational competencies for architecture, construction, and building systems. The results indicate that the majority of the competencies are proposed in the areas of thermal and humidity comfort and environmental protection, emphasising the crucial role of indoor climate regulation in supporting human health. This is consistent with research demonstrating that optimal temperature and humidity improve comfort, cognitive performance, and respiratory health [13,46]. Furthermore, the inclusion of competencies focused on energy efficiency and sustainable materials links environmental performance with human well-being, consistent with [10], which demonstrated that sustainable buildings significantly contribute to both occupant comfort and environmental health. This work significantly expands our understanding of these relationships in specific learning outcomes—such as calculating heat transfer coefficients, designing energy-neutral buildings, and conducting moisture analysis. In doing so, it moves from descriptive correlations to practical learning strategies. Important competencies are identified in areas such as acoustic comfort, air quality, and radiation protection, reflecting a previously noted gap in research on buildings and environmental health. The findings on natural light and the protection against e-smog also highlight the importance of research and the need for the development of skills in this area. Xue et al. [14] reported that green building solutions, such as access to daylight and views, significantly improve employee perceptions and health satisfaction. The limited number of competencies in these areas suggests the need to further integrate light and electromagnetic field exposure management and mitigation into educational content. These aspects are particularly important, as modern digital infrastructure and dense urban development increase exposure to artificial lighting and electromagnetic fields.

The practical implications and applications of the developed competence matrix provide practical guidance for curriculum designers, teachers, and policymakers. It can serve as a basis for revision vocational and higher education programmes to align them with current health and sustainability standards. It can serve as a reference point for updating architectural, construction, and installation programmes to align them with current standards of sustainable and health-promoting design. In practice, the matrix can support the integration of interdisciplinary modules in building physics, environmental psychology, and human physiology. Furthermore, aligning course content with the ecological certification framework increases professional relevance and encourages project-based learning that emphasises the health implications of design decisions. Subsequently, the integration of interdisciplinary educational modules that combine building physics, human health, and environmental sustainability has enabled the development of certification-compliant education, linking student competencies to professional standards such as WELL (Wellbeing Building Standard), BREEAM, and DGNB (German Sustainable Building Council). It is important to note that this increases professional awareness of the impact of design decisions on occupant health, supporting a new generation of professionals capable of creating buildings that are not only energy-efficient, but also promote physical and mental well-being. By systematically combining scientific evidence, competence development, and educational applications, this study advances the emerging field of healthy building education, bridging the gap between scientific knowledge and practical professional practice.

Given the complex and multidimensional relationship between the built environment and human health, this study highlights the need for long-term and periodic monitoring of the health impacts of buildings. Although this research identified key factors influencing human well-being and developed a framework of educational competencies, the findings are based on cross-sectional and pilot data, providing a preliminary but time-limited perspective on this issue. To ensure the robustness and relevance of the proposed competencies, longitudinal studies should be conducted to assess how integrating these competencies into curricula and professional practice impacts both the quality of the built environment and the health of the occupants in the long term. Such studies could include systematic monitoring of indoor environmental parameters—such as air quality, temperature, humidity, and acoustic comfort—along with health indicators and occupant satisfaction. In addition, a long-term monitoring plan is planned to assess the effectiveness of the curriculum changes implemented and to monitor the evolving relationship between building practices, technological innovations, and public health. This plan will include periodic evaluation cycles, involving educational institutions and industry partners, to adapt the competence framework to emerging scientific evidence and emerging environmental challenges. Although the scope of this study was limited to selected case studies and educational pilot implementations, its findings provide a solid foundation for future empirical validation and refinement of the proposed model. Expanding research to broader geographic and institutional scales will allow for a more comprehensive understanding of how educational strategies can enhance the health-promoting potential of the built environment.

The research results described in this publication are planned to be implemented in the curricula of the project partners' schools and universities. Implementation procedures have already been developed and tested in the experience of previous projects, including "Fit4BIM", " RecoverIND", and "Universal Design." The "Fit4BIM" project (2017–2020) resulted in, in addition to the competence matrix, lesson plans and educational publications for teachers and students [119,120]. The content developed as part of the project is still present in the curricula of architecture and construction programmes at the University of Technology. Thanks to this preparation, graduates find employment that utilises their acquired competences in Building Information Modelling. The "RecoverIND" project (2021–2023) resulted in video tutorials on the use of modern technologies in building renovations (not only industrial buildings). The developed materials are used during classes in architecture and construction programmes at the University of Technology. Students use the acquired skills not only in their professional careers, but also in their scientific development by publishing the results of their research [121]. As part of the project "Universal Design" (2019–2022), activities were implemented to improve the quality of education and the competences of participants in the teaching process in the field of barrier-free building design. The laboratories were equipped with teaching aids, including ageing simulators and wheelchairs, and both students and university staff participated in universal design training. Mandatory universal design courses were introduced into the curricula of the following fields: architecture, interior design, construction, sustainable construction, and environmental engineering. These activities aimed to promote equality and accessibility in the educational process and to develop competences that support the creation of user-friendly spaces for all users, regardless of age, ability, or need. The acquisition of new competencies is observed in the increasing number of theses that utilise the acquired knowledge.

During the "Co4Health" project, students eagerly participated in workshops and webinars that spread the results. They are focused not only on technical aspects, but also on the impact of indoor environments on human health and well-being. They are increasingly proposing topics related to theses in their theses, thus seeking modern yet sustainable solutions. The following are sample topics for student theses in selected fields of study:

- Architecture: daycare centre for people with dementia, modular temporary hospital, design of healthcare facility;
- Construction: analysis of the accessibility of a laboratory room on the university campus, senior-friendly building;

- Sustainable construction: energy analysis of a single-family building subjected to thermal modernisation, thermal modernisation of an existing single-family building to a passive standard;
- Environmental engineering: climatic comfort for athletes and ventilation of sports rooms, air preparation processes for swimming pools and offices, plants as an element of the ventilation system.

Furthermore, it is worth emphasising that students actively participate in conferences, seminars, and fairs dedicated to healthy construction, such as the Accessibility Forum, Hospital Construction Conference, "Poleco", and "Budma" fair. Participating in these events provides them with an additional source of knowledge and an opportunity to exchange experiences with experts. The topics covered in classes and during these events are very important for students from both a scientific and practical perspective, but above all, they motivate them to develop towards designing sustainable living environments and health-promoting design.

6. Conclusions

Based on the analysis conducted, factors that influence the health-promoting impact of buildings were identified and a set of competencies was developed that should be incorporated into the curriculum in technical schools. Obtaining construction-related qualifications that promote health requires changes in curricula. These changes can be implemented in the following three areas: knowledge, skills, and social competences. The proposals were prepared in the form of a competence matrix, divided into individual levels of education (Supplementary Materials). Professions whose curricula could be modified were also identified.

Based on the analysis, the study identified key factors that influence the health-promoting impact of buildings and translated them into a structured set of competencies that should be incorporated into curricula in technical and vocational education institutions. The results show that achieving health-promoting qualifications in construction requires targeted modifications to curricula in the following three interrelated areas: knowledge, skills, and social competences.

To implement these changes, a comprehensive competence matrix was developed (which will be available after the completion of the project on the website https://co4health.eu/), outlining the expected learning outcomes and their relationship to each educational level. This matrix can serve as both a diagnostic and planning tool, allowing educators and policymakers to adapt curriculum content to contemporary expectations of sustainable and health-promoting building practices. Furthermore, the study identified specific construction-related professions whose curricula could be improved by incorporating principles of healthy building design, management and operation.

The competence framework covers key areas of healthy building, including thermal and humidity comfort, indoor air quality, acoustic and visual conditions, and environmental protection. Integrating these areas with education can strengthen professional competencies in the design and maintenance of buildings that promote physical well-being, psychological comfort, and environmental sustainability.

In general, this study contributes to the discourse on healthy buildings by bridging the gap between scientific evidence on indoor environmental quality and educational practice. It provides a model for integrating health promotion principles into technical education, thereby supporting the development of a workforce capable of addressing emerging public health and sustainability challenges in the built environment. Future research should expand the empirical base of this framework, test its validity in different national and institutional contexts, and assess its long-term impact on professional competences and design outcomes.

A summary of the health building issues addressed in the competence matrix is presented in Figure 3. The graphic is designed as a puzzle to demonstrate that each element, representing a different aspect, contributes to the overall health-promoting impact of a building. The skills for healthy building are interdisciplinary in nature, combining knowledge and skills from multiple disciplines—such as building physics, environmental engineering, architecture, ergonomics, ecology, and human health sciences. The graphic aims to present a comprehensive competence profile for the designer, contractor, and building manager.

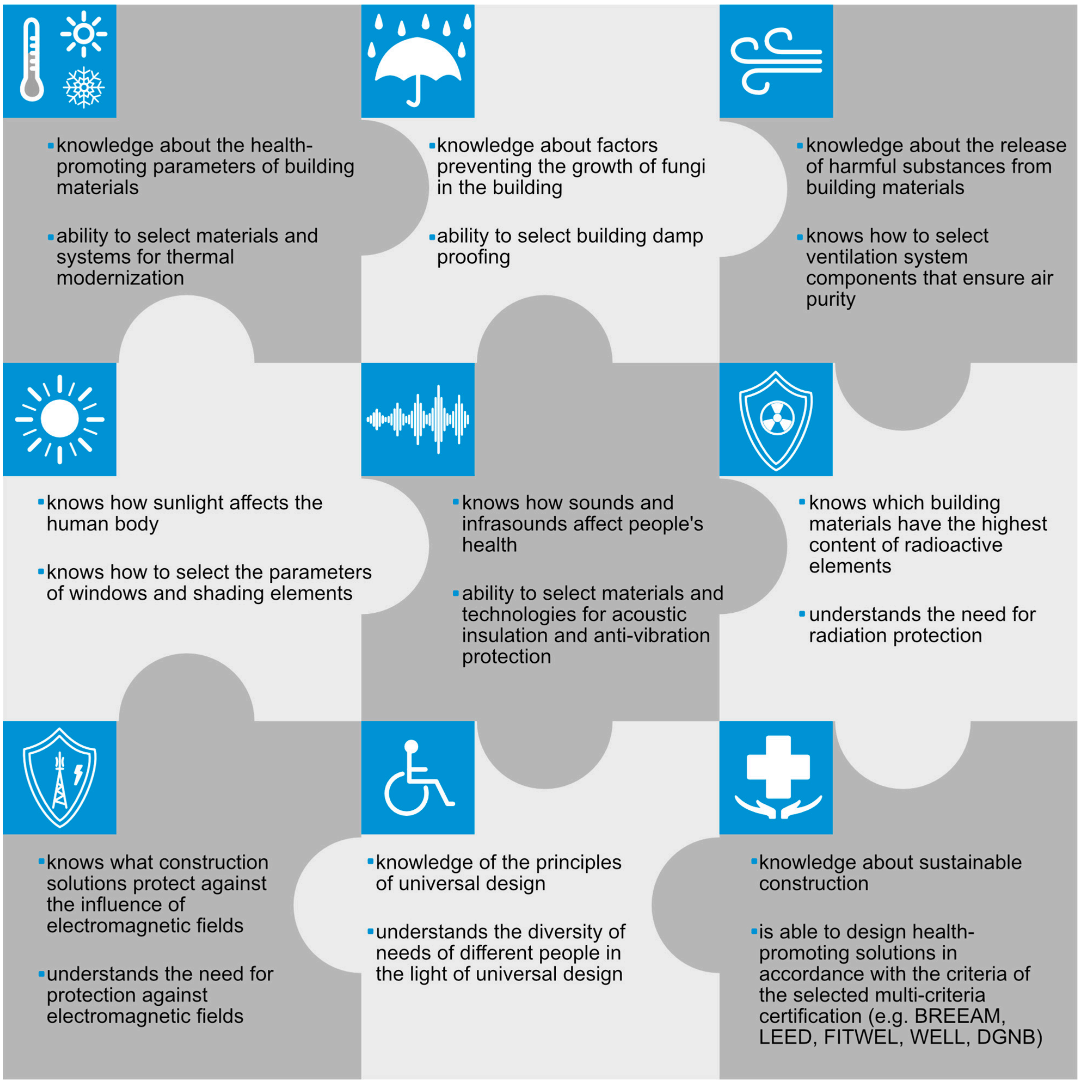

Figure 3. Selected most important competences in the field of knowledge, skills, responsibility, and autonomy related to the issues of healthy construction.

Designers and contractors of buildings should know what values the parameters of individual factors should have in the areas of thermal and humidity comfort, health-promoting factors rewarded in multi-criteria analyses assessing the impact of a building on the environment, acoustic comfort, clean air, radiation protection, natural light, and e-smog protection, and how to adapt buildings for everyone, regardless of their ability, so that they have a health-promoting effect.

The prepared competence matrix can be supplemented with additional aspects as knowledge about the impact of buildings on users develops.

By contextualising health factors related to buildings within an educational framework, this study moves beyond descriptions of healthy buildings toward a competence-based model that supports both teaching and professional application. Integrating human health into building and design education not only fills a significant gap in scientific knowledge, but also lays the foundation for the development of a healthier and more sustainable built environment.

Based on the analysis conducted, which includes results from medical research, technical regulations, and expert experience, a number of practical conclusions can be drawn about the impact of buildings on human health, which can be used in the planning of educational offerings and legal regulations. The results of numerous studies point to the common conclusion that the quality of the indoor environment—including thermal and humidity comfort, ventilation air quality, noise attenuation, spatial ergonomics, and access to natural light—affects people's well-being, concentration, and work performance, and can also be related to overall health of occupants.

Based on the analyses conducted, several directions of change can be proposed, as follows:

- In education:
    - Introducing content on the health-promoting parameters of buildings and the indoor environment to the curricula of technical schools and architectural and engineering studies,
    - Preparing interdisciplinary courses and workshops in which students of various fields of study will learn the principles of health-promoting building design, e.g., by jointly developing health-promoting building designs,
    - Expanding the offer of professional training and certification (in line with the principle of lifelong learning) in the field of "healthy building design".
- In regulations and legal provisions:
    - Review and possible update of building regulations and standards in the project partner countries based on the results of the latest scientific research on, for example, indoor air quality, permissible noise levels, and minimum parameters of natural lighting and thermal comfort,
    - Developing rules for assessing the impact of a building on human health, and, in the long-term, developing recommendations, as well as certification of a "healthy building".

Actions that increase awareness of the impact of buildings on human health and develop skills in designing, building, and maintaining "healthy buildings" can, in the long run, contribute to improving the quality of life and health of people, which can reduce the costs of the healthcare system.

A review of the literature, including the results of medical research, provided information on the impact of the indoor environment in a building on human physical and mental health. The study also analysed applicable technical regulations—architectural and construction. Based on the combination of these two areas of knowledge, conclusions were drawn about the impact of building parameters, such as thermal comfort, access to daylight, ventilation, and acoustics, on employee well-being and productivity. Using results from multiple disciplines enabled an integrated approach to the problem and the formulation of recommendations based on scientific evidence and practical experience.

The study concludes that it is necessary to develop interdisciplinary collaboration and improve cooperation mechanisms. It is proposed to organise inter-institutional research teams that integrate scientists from various research fields and practitioners from companies. It would also be beneficial to create a common communication platform to connect specialists from different fields into teams. Future research should include user opinions on indoor air quality in buildings with different indoor climate control methods, including those using IoT sensors and controllers, to better understand the subjective feelings and needs of people in these environments.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su172210304/s1. Table S1. Competencies related to healthy construction for levels 3 and 4 of education.

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Abbreviations

The following abbreviations are used in this manuscript:

BIM	Building Information Modelling
BREEAM	Building Research Establishment Environmental Assessment Method
DGNB	Deutsche Gesellschaft für Nachhaltiges Bauen—German Sustainable Building Council
EQF	European Qualifications Framework
HBB	Healthy Buildings Barometer
HVAC	Heating, Ventilation, Air Conditioning
IAQ	Indoor Air Quality
ICNIRP	International Commission on Non-Ionizing Radiation Protection
IEEE	Institute of Electrical and Electronics
ISCED	International Standard Classification of Education
LEED	Leadership in Energy and Environmental Design
VET	Vocational Education and Training
VOC	Volatile Organic Compounds
WELL	Wellbeing Building Standards

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