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Citation for the original published paper (version of record):
Cabovska, B., Teli, D., Ekberg, L. (2025). Building certification schemes–A way towards better IAQ and thermal comfort in schools? A
critical review of schemes used in Northern European countries. Building and Environment, 275.
http://dx.doi.org/10.1016/j.buildenv.2025.112786

Building and Environment 275 (2025) 112786

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Building certification schemes–A way towards better IAQ and thermal comfort in schools? A critical review of schemes used in Northern European countries

Blanka Cabovská [a,*], Despoina Teli [a], Lars Ekberg [a,b]

[a] Chalmers University of Technology, Division of Building Services Engineering, Department of Architecture and Civil Engineering, SE-412 96, Göteborg, Sweden
[b] CIT Renergy AB, SE-41258, Göteborg, Sweden

A R T I C L E I N F O

Keywords:
Building certification
School buildings
Thermal comfort
Indoor air quality
Nordic countries

A B S T R A C T

Many research studies have shown that the quality of indoor environment in school buildings is poor, with low ventilation rates being the most common issue. In the recent years, the interest in certification system have been constantly growing and their use have become more common not only in offices, but also in other types of buildings including educational. The aim of this critical review is to provide a constructive analysis of selected building certification systems and to discuss whether their utilisation can lead to improvements in the currently generally unsatisfactory indoor environment conditions in schools.

Several certification systems (BREEAM, LEED, DGNB, Miljöbyggnad and Svanen), which are used in the countries of Northern Europe (Sweden, Norway, Denmark and Finland), are subject of a detailed examination. Both systems used for design and construction of the buildings and systems for buildings in operation are included. The focus is on the criteria related to thermal comfort and indoor air quality, which are also compared with relevant national requirements.

All systems include criteria that focus on thermal comfort and indoor air quality; however, the scope and level of detail differ. Moreover, the stage of the building life cycle in which the systems is applied is also crucial. The identified advantages and disadvantages of the use of certification systems as well as the elements and factors that would merit greater attention in the case of school buildings are also discussed.

1. Introduction

The school environment is a highly complex system with many factors influencing the air quality in the classrooms. Air pollution sources, thermal comfort, mobility of the school children and building characteristics belong to primary factors influencing the air quality, with many more interrelated parameters, e.g. distance from road, cleaning, classroom activities, outdoor pollution sources and more, as described in the review by Salthammer [1]. Given that children spend a substantial proportion of their days inside these buildings, schools represent a building category of a special interest. Moreover, the immaturity of their immune systems makes them even more vulnerable to the risks that the indoor environment can pose [2]. Particulate matter (PM) originating from various sources both indoors and outdoors, are often being identified as a major contributor to indoor air pollution. Inhalation of PM may pose various health concerns and issues [3]. Volatile organic compounds (VOCs) represent another category of air pollutants that have been linked to adverse health effects on building occupants, including asthma, allergies or respiratory health problems. VOC concentrations in newly built or recently renovated schools may be significantly higher than the concentrations outdoors [3]. Nitrogen dioxide (NO_2) levels in classrooms are often associated with outdoor levels, emphasizing the importance of the site location and outdoor air quality [4]. Ozone (O_3) levels are usually lower in classrooms than outdoors [5]. Carbon monoxide (CO) is mainly produced in schools where combustion processes or smoking is allowed [3]. Radon also poses another significant threat to indoor occupants, including children in educational institutions, as it is now well documented that this natural radioactive gas belongs to the leading causes of lung cancer. [6]

Despite its extraordinary importance, the literature provides considerable evidence indicating that indoor air quality (IAQ) in many school buildings is poor, with ventilation rates well below the minimum

* Corresponding author.
E-mail address: blanka.cabovska@chalmers.se (B. Cabovská).

https://doi.org/10.1016/j.buildenv.2025.112786
Received 29 October 2024; Received in revised form 4 February 2025; Accepted 24 February 2025
Available online 1 March 2025

required values, which was confirmed in a literature review focusing on ventilation problems in schools [7]. This results in indoor environments with elevated concentrations of carbon dioxide (CO_2), which is often used as a proxy for indoor air quality, as it is typically correlated with concentrations of other pollutants. Furthermore, the CO_2 levels in classrooms are associated with pupils' performance, as demonstrated in a study by Wargocki [8].

A literature review focusing on the IAQ and health in schools [3] identified and discussed several pollutants of a major concern in school buildings, including VOCs, PM, O_3, NO_2 and CO. In addition, the same review also mentioned that pollutant concentrations in schools were higher than in residential or commercial buildings, and proposed several actions needed to improve the IAQ in classrooms. These included deepening occupants' understanding of IAQ, implementing source control strategies and optimising the building design itself in order to balance the energy efficiency and IAQ in building.

In most schools worldwide, natural ventilation is the dominant strategy [3], in which windows and other openings play an important role. However, they are often kept closed to avoid thermal discomfort or other disturbances from outdoor environment, such as noise, resulting in inadequate ventilation rates. All of this suggests that creating the appropriate indoor conditions by the means of window opening is challenging, especially when combined with the efforts to reduce energy use.

Problems with poor IAQ in classrooms have been further exacerbated over recent years due to a one-sided focus on building energy efficiency, notable increase in efforts to reduce greenhouse gas emissions and to combat the negative consequences of climate change. In the building sector, the focus was initially on improving the energy efficiency of buildings, but shortly after it shifted towards the whole life cycle of the buildings. Building certification schemes were mainly driven by such environmental initiatives [9]. However, efforts to improve the energy efficiency of buildings without parallel efforts to maintain or improve IAQ have gradually led to a deterioration in the quality of the indoor environment. In particular, improvements in buildings' airtightness had, in some cases, negative effect on the ventilation rates, resulting in insufficient air change rates and accumulation of hazardous pollutants in indoor environment [10,11]. Public buildings, including schools, have also experienced such energy efficiency improvements leading to IAQ deterioration [12].

Thermal comfort (TC) is one of the most important aspects of indoor environmental quality (IEQ) due to its impact on occupant satisfaction, well-being and performance. Many studies have reported a difference in thermal preferences between adults and children, which has been summarized in reviews by both Sabrizadeh [3] and Zomorodian [13]. The evidence suggests that children prefer cooler environments than adults and are more sensitive to warmer conditions. However, as Zomorodian describes [13], large differences in thermal neutralities have been observed even in studies conducted in the same climate zone. The same review also highlights the problem with overheating in school classrooms due to high solar gains from large windows, high levels of thermal insulation, airtight buildings and insufficient cooling as the windows are often closed to prevent external noise and draughts. Another common attribute of school classrooms that may contribute to overheating is the high occupant density. Overheating is becoming an issue even in the countries with colder climates, such as Sweden, as discussed in a report by Österbring [14]. Sabrizadeh [3] also emphasises that the possibility to adjust clothing and environmental variables or modify activity level to adapt to the actual thermal conditions is very limited for children during school lessons, as they are usually passive recipients of the conditions. Teachers, being mostly responsible for adjusting the environmental conditions in classrooms, are more likely to behave according to their own thermal preferences than those of the pupils.

Overall, school environments face significant challenges and require special attention in order to ensure a good indoor climate that contributes to children's well-being. If higher demands need to be met, a way for improved conditions in schools may be the wider adoption of building certification systems, provided these adequately address the factors most significant for this special type of building.

1.1. Building certification systems

The popularity of building certification systems has increased markedly in recent times, with both the number of certification systems and the number of certified buildings growing at a rapid pace. The development of the first schemes began in the 1990s and continued with a boom in the 2000s, when many local Green Building Councils and local certification schemes were also established [9]. To date, the World Green Building Council webpage lists about 60 certification systems [15]. The total number is likely to be much higher, as many systems are not administered by this organisation.

The common aim of the building certification systems is to recognise and reward companies and organisations building and operating buildings that meet certain sustainability requirements or standards [15]. The systems usually address many topics related to sustainability, including indoor environmental quality. Having the similar aims, the schemes may differ in their approach, scope, type of building or life-cycle phase they can be applied to. Many studies have attempted to compare different certification systems [16–19], including those focusing on aspects related to health and well-being [20–26]. Results of such comparisons typically highlight and critique the discrepancies in terms of the issues considered, the relative importance assigned to different topics and the rating strategies employed in different systems. Even though they have different aims and look at the certification systems from different perspectives, none of the reviews focused on schools.

Certification systems are frequently employed to certify office or residential buildings, but they can also be applied to school buildings. Overall, interest in school building certification is lower than that of office buildings, as evidenced in databases of certified buildings. Nevertheless, certain US states and cities even mandate that new public buildings, which often includes school buildings, should be LEED certified [27]. In Sweden, despite not being mandatory, many new school buildings have been certified using the local certification system Miljöbyggnad [28].

As the certification systems also address aspects related to IAQ and TC, the question is whether their wider use could lead to improvements in the current overall unsatisfactory IEQ in schools. Literature investigating the IAQ and TC related aspects in certified buildings is quite extensive. A systematic review focusing on the impact of green buildings' IEQ on occupants' health and satisfaction showed mixed conclusions not exclusively supporting the claim that green buildings are generally superior to their non-green counterparts in terms of health and overall comfort [29]. However, the literature assessing the conditions in certified compared to conventional school buildings is quite modest. Some studies focus on higher educational level institutions such as universities [30,31], however, these buildings are characterised by different occupancy and operational patterns compared to primary or secondary schools, in many aspects more similar to office buildings.

Still, there is some literature analysing the differences between conventional and certified school buildings. Ventilation rates in 10 conventional and 27 certified US schools did not significantly differ, as concluded in [32]. Instead, it was, among others, the HVAC design, maintenance, operation, or teachers' behaviour that governed the ventilation rates and CO_2 concentration levels in classrooms. A study by Zhong [33] analysed 144 classrooms of 37 conventional and certified recently constructed or renovated school buildings in US Midwest, concluding that no difference in VOC concentrations was found. In addition, they found that the VOC concentrations were mostly low compared to levels measured in previous decades. A study by Issa [34] compared a sample of 10 conventional, 20 retrofitted and 3 certified Toronto schools in terms of absenteeism, performance and occupants' satisfaction with indoor environment. Overall, the teachers were more satisfied with aspects related to IAQ and TC in certified schools. Students and staff absenteeism improved by several per cent, as well as students' performance, however these results were not statistically significant.

The findings from these studies suggest that the differences between conventional and certified buildings are not conclusive. Further research and analyses are needed to understand whether the use of certification systems in schools can really deliver desired benefits in terms of better occupant satisfactions and improved IAQ and TC conditions or whether there are gaps in their setup and implementation that pose limitations to achieving real improvements.

1.2. Aims and objectives

This work is part of a project investigating IAQ and TC in Swedish school buildings, therefore the analysis focuses on Northern European countries with emphasis on the Swedish context.

The situation in the Nordic countries differs from that of the rest of Europe. The SINPHONIE study [35] indicated that the use of mechanical ventilation systems in schools is much more common in the northern part of Europe compared to the rest of the continent. In Sweden, most schools are equipped with balanced mechanical ventilation systems [36]. Nevertheless, a report published by Public Health Agency of Sweden showed that 15 % of the Swedish schools had "poor" or "rather poor" IAQ [37]. An extensive field study of 45 primary school classrooms in Gothenburg [38] found that even though the overall IAQ was good at median level, the majority of classrooms, which included even those ventilated mechanically, had ventilation rates below the national requirements. These findings suggest that even though legal requirements related to IAQ and TC in schools are in place, these are still not met in practice in all schools.

This paper aims to contribute with critical perspectives on ways building certification schemes can be used or adjusted in order to promote better IEQ in schools. The aims of this paper can be summarised as follows:

1. To review the criteria related to IAQ and TC included in the certification schemes used in Northern Europe.
2. To critically evaluate the way school buildings are addressed in the IAQ and TC criteria of certification schemes.

Specific research questions of this paper are:

1. Which requirements, if any, are added in the building certification schemes compared to national building requirements?
2. Are any post-construction and/or post-occupancy verification procedures, included in the building certification schemes to ensure that the criteria are met?
3. Which are the main advantages and/or disadvantages of using building certification schemes in relation to fulfilling national building requirements and post-construction and/or post-occupancy procedures for school buildings?

2. Methodology

2.1. Review method

A methodological approach for the analysis in the paper is presented in this section. The review type chosen for this paper is a critical review, which was conducted in accordance with the methods described in [39] and [40]. This review type employs a critical analysis of existing literature related to the topic with the objection to reveal potential strengths, weaknesses and contradictions. Additionally, its aim is to strengthen the development of knowledge by suggesting future research focuses and directions, which aligns with the aims of this paper.

Certification manuals were reviewed, and chapters or issues related to IAQ and TC were selected for further analysis. The analysis part comprises the description of the manner in which IAQ and TC are addressed in the selected certification schemes. More specifically, the IAQ and TC sections in the schemes are compared with the list of factors which are considered as necessary prerequisites to design and operate buildings with optimal IAQ and TC conditions. Table 1 provides an overview of these factors.

2.2. Selection of the certification systems

The World Green Building council administers over 60 building certification systems [15], but the total number is probably much higher. The following criteria were used to select the certification systems included in this review:

1. The certification scheme can be used for the construction of school buildings.
2. The certification evaluates the holistic building performance.
3. The certification scheme includes IAQ and/or TC criteria.
4. The certification scheme is used in Sweden or other Nordic countries (Denmark, Finland, Norway). These countries have similar climatic conditions and similar construction standards and practices.
5. The information and manuals are publicly available.

In order to find out which certification schemes are used in Sweden and other Nordic countries, the webpages of local green building councils were examined [41–44]. This resulted in the selection of BREEAM, LEED, DGNB and Miljöbyggnad. Although not administered by any of the local green building councils, Nordic Swan Ecolabel (Svanen) [45] was also added as it is used in all countries of interest. The most recent version of all systems available at the time of writing has been used. Where possible, the version adopted for Sweden and educational buildings as well as the criteria valid for educational buildings have been used in this review.

There are more certification systems being used in the countries of Northern Europe. However, these are not included in this review, as they do not fulfil the selection criteria. One of such examples is WELL [46], which is a certification system heavily focusing on health and wellbeing aspects. However, unlike the selected systems, it does not evaluate the holistic building performance, as it does not include topics covering

Table 1
Design, operation and verification aspects influencing the TC and IAQ in buildings.

	TC	IAQ
Design	• Outdoor thermal climate • Quality of building envelope (opaque and transparent parts) • Window to wall ratio • Window orientation • Solar shading • HVAC system control	• Outdoor thermal climate and outdoor air quality • Building materials • Activities and equipment in the building (cooking, smoking, use of printers etc.) • Ventilation strategy and design • Air filtration • Outdoor air exchange • Ventilation system control
	• Availability of occupant control	
Operation	• Target values for TC indicators (temperature, RH)	• Target values for pollutants concentration (PM, VOC etc.) • Target values for CO_2 concentrations
	• Maintenance strategies • Building management routines – HVAC operation, materials and products choices • Communication between building management and users (feedback, fault reporting, surveys etc.)	
Verification	• Post-occupancy measurements incl. temperatures • Post-occupancy surveys	• Post-occupancy measurements of pollutants

other aspects of building design, construction and operation stages, such as LCA, water use, project and construction management, choice of materials, waste management and others. Another example of systems excluded from this review is Passive House certification [47], as it focuses primarily on design and construction aspects of the building with the aim to minimise its energy demands. It lacks inclusion of IAQ and TC requirements, even though it can have positive effect on IAQ and TC, for example in terms of use of the mechanical ventilation systems and improved TC thanks to well-insulated envelopes.

As the selected systems offer different versions suitable for different building life-cycle stages, both version for new construction and buildings in operation were selected for this review. Table 2 provides an overview of the certification systems included in this review.

Table 3 shows an overview of educational buildings in Nordic countries certified with the most common systems used in these countries.

Each of the selected certification systems uses different terminology to describe its structure. Table 4 provides an overview of this terminology used in the selected certification systems. This terminology is further employed in the respective descriptions and analyses.

3. Analysis

The analysis part of this paper comprises analysis of the national IAQ and TC requirements and the analysis of the selected certification systems. This is further divided into two sections – systems focusing on design and construction and systems focusing on building operation.

Table 2
Overview of the selected certification systems and their version used in this review.

Building certification system	Year of introduction and country of origin	Version used in the comparison	Notes
BREEAM	1990, UK	BREEAM-SE v. 6.0 New Construction [48]	In Norway, local adapted version BREEAM-NOR v. 6.1 [49] is used
		In-Use International v.6.0.0 [50]	
LEED	1998, USA	BD+C Schools v.4.1 [51]	
		O+M (Operation + Maintenance) v.4.1 [52]	
DGNB	2009, Germany	New Construction version 2023 [53]	Where possible, requirements related specifically to educational buildings were selected for analysis
		Buildings in Use version 2020 [54]	
Miljöbyggnad	2009, Sweden	v. 4.0 [55]	
		iDrift 2.0 [56]	
Svanen (Nordic Swan Ecolabel)	1989, Nordic countries	089 New Buildings version 4.3 [57]	Where possible, requirements related specifically to Sweden and educational buildings were selected for analysis
		No specific manual alternative for buildings in operation	

3.1. Review of the IAQ and TC requirements

Requirements related to IAQ and TC in the four Nordic countries are summarized in Table 5. Values stated are valid for primary and secondary school buildings. Requirements for kindergartens are not included.

All countries, except for Denmark, set requirements for exact ventilation rates in a form of required volume of air per person and per floor area. Ventilation requirement in Denmark is regulated by setting the upper limit of CO_2 concentration. Minimum and maximum temperatures are set in all countries, but the exact values differ within an interval of few degrees. Finland states exceptionally high maximum temperature during non-heating season. Norway and Finland limits concentrations of certain pollutants indoors. However, in Sweden and Denmark, no such requirements are stated. One explanation to the fact that the pollutants are often omitted in national legislations is that CO_2 is generally considered as indicator of air quality, and in many cases (even though not in all) is correlated with other pollutants. Moreover, it is relatively simple to measure its concentration compared to other pollutants. These often require use of expensive measurements equipment or laboratory analysis. No assessment and verification methods, such as measurements or occupant surveys, are generally required.

3.2. Certification systems focusing on building design and construction

This section of the paper describes the selected certification schemes focusing on building design and construction, and how the IAQ and TC are addressed within them, followed by the comparison of selected indicators and assessment methods.

3.2.1. BREEAM-SE

The British Research Establishment Environmental Assessment Method (BREEAM) is one of the oldest certification systems. Established in the UK in 1990s, it has since been adopted in numerous countries worldwide. Currently, many national adaptions are available, including the Swedish version.

BREEAM is divided into a number of environmental sections, which include several assessment issues describing in detail the criteria for obtaining credits. The number of credits obtained per environmental section is then weighted to calculate the final score and to determine the final rating, from pass (≥30 %), good (≥45 %), very good (≥55 %), excellent (≥70 %) to outstanding (≥85 %). BREEAM is relatively flexible allowing for the offset of non-compliance in one area to compliance in another one. Certain minimum standards are set in key performance areas, which must be fulfilled in order to receive any certification grade. However, none of the requirements included in both TC and IAQ related issues are included in these minimum standards. This statement is valid for both the Swedish and international version. Interestingly, the Norwegian version is different, setting more mandatory requirements also within the topic of IAQ. In addition, the higher the desired final rating, the more mandatory requirements are set.

IAQ and TC are included in the Health and Wellbeing (HEA) section, as two assessment issues – Indoor Air Quality and Thermal Comfort.

Credits are awarded for the compilation of an IAQ plan for the building and for the fulfilment of the criteria related to providing sufficient amount of fresh air as specified in the Swedish Building Code [58] and fulfilling some other requirements relating to ventilation. More credits can be obtained when low-emitting materials or products are used and demonstrating that the required limits are met by conducting post-construction formaldehyde and VOC measurements. Possibility to adopt natural ventilation strategies in the future is also awarded a credit. CO_2 or air quality sensors are required in buildings or building portions which are subject to large and unpredictable or variable occupancy. Building envelope quality is included only in the assessment issues focusing on reduction of energy use.

In the topic of TC, credits are awarded for proving that the required

Table 3
Number of certified school buildings in the countries of interest.

	Sweden	Norway	Finland	Denmark	Notes
BREEAM New Construction	3	38	0	0	Project type – education, includes all types of educational buildings
BREEAM In-Use	58	20	123	2	
LEED	1	0	5	0	LEED BD+C Schools
LEED O+M					Number could not be obtained from the database as building type cannot be distinguished in the database
DGNB				20 (19 new construction + 1 renovation), 25 (daycare)	New construction + renovation
DGNB Buildings in Use				1	
Svanen	35 (13 schools + 22 daycares)	3 + 2	6 schools + 4 daycares	5 + 21 (daycare)	
Miljöbyggnad	459 (of which 191 verified, 267 preliminary certified)	*Not used in these countries*			All types of educational institutions (including kindergartens and universities)
Miljöbyggnad IDrift	86	*Not used in these countries*			All types of educational institutions (including kindergartens and universities)

Notes: The data in Table 3 were obtained from the respective online databases on the 4th of October 2024 and from the Swedish Green Building Council during October 2024.

Table 4
Terminology used in the review paper and in specific certification systems.

	Grading	Mandatory requirement	Structure	
BREEAM	Credit	Minimum standard	Environmental section	Assessment issue
LEED	Point	Prerequisite/ Required	Credit category	Credit
DGNB	Point	–	Topic	Criterion
Miljöbyggnad	–	–	Indicator	–
Svanen	Point	Obligatory requirement	Criterion	–

PMV and PPD indices are met by conducting thermal simulations. A credit is awarded when PMV and PPD are met also for future climate scenarios. Furthermore, additional credit is awarded when the thermal simulation informed the temperature control strategy for the building and users, and that the heating and cooling strategy was effectively designed, addressing building zoning, degree of occupant control and mutual interaction of the systems.

Further aspects relevant to topics of IAQ and TC are included in the section Management as a part of assessment issue Aftercare. This issue requires post-occupancy evaluation, which should be conducted one year after the initial building occupation. Among others, it should also include feedback on internal environmental conditions.

3.2.2. *LEED BD+C schools*

Since its inception in 1998, the Leadership in Energy and

Table 5
Requirements related to IAQ and TC in school buildings in Sweden, Norway, Finland and Denmark.

Indicator	Limit values			
	Sweden	**Norway**	**Finland**	**Denmark**
Ventilation rates	0,35 l/m^2.s + 7 l/person.s	Min. 7,2l/s.personFresh air to dilute pollution from materials and products: • 0,69 l/s.m^2 when in use • 0,19 l/s.m^2 when not in use	0,35 l/s.m^2 + min. 6 l/s.person	Not less than 0,35 l/s.m^2 when the room is occupied *Exact rate per person not given, only requirements for CO_2concentration*
CO_2 concentration**	1000 ppm	*Value not specified**	1150 ppm above outdoor concentration (~1550 ppm indoors)	1000 ppm
Temperature, min	18 °C	19 °C (operative temperature)	20 °C	18 °C
Temperature, max	24 °C (operative temperature during heating season) 26 °C (air temperature in summer)	26 °C (operative temperature)	26 °C (heating season) 32 °C (non-heating season)	25 °C
Pollutants concentration in indoor air (PM, VOC..) - yes or no	*Not given****	PM10, NO_2****	PM2.5, PM10, CO, formaldehyde, VOC, TVOC****	*Not given*
Sources of requirements	Swedish building code [58] Public health agency of Sweden [59,60] Swedish work environment authority [61]	Norwegian building code [62] The Norwegian labour inspection authority [63]	National supervisory authority for welfare and health [64,65]	Danish building code [66] The Danish working environment authority [67]

Notes:.
* However it is recognized that values above 1000 ppm is a sign of lower ventilation rates than recommended.
** CO_2 concentration that should not be exceeded more than occasionally during occupied time.
*** The Swedish building code only requires that the level of pollutants must not exceed the applicable limit values for outdoor air.
**** For details on limit values and measurement protocols, we refer to the cited standards and documents issued by respective authorities.

Environmental Design (LEED) has expanded to become the most widely used certification system [68]. Even though the system originates in the United States and is primarily based on US legislation and standards, there are often options to follow different standards (such as European) to facilitate the use of LEED in other parts of the world.

LEED BD+C is intended for use in new construction and major renovation projects. It offers a range of manual options specially tailored for various building types, including schools. Levels of certification that can be achieved are certified (40–49 points), silver (50–59 points), gold (60–79 points) or platinum (80+ points). Points can be awarded for meeting criteria specified in credits, which are grouped into credit categories. Many credit categories include prerequisites, which summarise the mandatory requirements needed to qualify for the certification. LEED often offers more pathways or options to meet certain credit criteria, so that the design can be flexible and adjusted to local conditions.

Issues related to IAQ and TC are included in credit category Indoor Environmental Quality. Prerequisites in this category emphasise the total prohibition of smoking on site and the obligation to meet minimum IAQ performance standards by providing sufficient ventilation.

Points can be awarded for meeting the requirements set in several credit categories. One of these is the preparation of construction IAQ management plan, which should include practices and procedures related to IAQ during the construction and preoccupancy phase. Other credit categories include focus on the use of low-emitting materials and other source-control strategies, such as use of entryway systems, increased ventilation by 15 or 30 % above the minimum rate, operable windows, prevention of cross-contamination, monitoring CO_2 or other air contaminants where relevant. Among assessment methods, post-construction PM and VOC testing is included. However, this can be substituted by conducting “building flush-out”, e.g. ventilating the building by prescribed amount of air either before or during occupancy. Regarding TC, a point is awarded when specified requirements for thermal comfort design (linking to ASHRAE standard) and control, such as individual TC control, are met. LEED also includes credits that focus on site assessment, including assessment of solar exposure, solar shading, average monthly precipitation and temperatures, and proximity to major sources of air pollution. Quality of building envelope is a part of energy performance optimization credits.

3.2.3. DGNB New Construction

The certification system Deutsche Gesellschaft für nachhaltiges Bauen (DGNB) was first used on the market in 2009 and has since become a market-leading German certification system [69]. It is used mainly in German-speaking countries, but also in other countries such as Denmark, Croatia and Spain. DGNB offers separate system variants for different building life-cycle stages, such as new construction, buildings in use or renovations.

The DGNB New Construction system is divided into six main topics, each of which covers different aspect of sustainable building – environmental quality, economic quality, sociocultural and functional quality, technical quality, process quality and site quality. The number of points achieved in each topic is weighted differently to give the overall score. The final building grade (bronze, silver, gold, platinum) is awarded based on the total performance index and minimum performance index. The total performance index is calculated using all six topics, while the minimum performance index must be achieved in the three main topics (environment, economy and socio-cultural quality) to ensure a certain level of quality. Apart from that, minimum requirements for all buildings are set in certain assessment topics, being even stricter for those aspiring for the highest certification level. In addition to the points awarded in the specific topic, it is possible to obtain additional points by fulfilling certain “Agenda 2030″ criteria, providing innovative solutions, or focusing more on aspects of the circular economy.

IAQ and TC related issues are included in the sociocultural and functional quality topic. Requirements related to IAQ includes conducting measurements to prove that limit values for VOC emissions have not been exceeded and achieving desired ventilation rates. Extra points can be obtained when the IAQ is verifiably improved by alternative and innovative solutions. Regarding ventilation, the assessment is based on DIN EN 16798–1. TC is evaluated with respect to the period of the year, with specific criteria set for both cooling and heating period. Operative temperature, draft, radiant temperature asymmetry and relative humidity are assessed. TC evaluation is generally in line with DIN EN 16798–1 and DIN EN ISO 7730. An additional point can be achieved when the climate predictions for 2030 and 2050 are taken into account. Summer heat protection is also considered by requiring the compliance with relevant chapter in German standard DIN 4108–2. Additionally, source elimination strategies are included in the topic Environmental quality in a form of limiting hazardous and polluting substances in materials.

Topic Site quality includes the assessment of local environment. Among others, local air quality (PM and NO_2 levels) should be assessed. Building envelope design is also a subject of assessment in the topic Technical quality, including focus on heat transfer coefficients, thermal bridges, airtightness and summer heat protection. The same topic also encourages the design team to focus on the integration of passive building concepts and strategies, such as design of highly compact building structure, the use of components with high storage masses, balanced proportion of window areas, structural solar protection to prevent direct sunlight during spring and summer season. Even though the main motivation is the low energy demand, the positive impact these strategies can have on TC and IAQ are also acknowledged.

3.2.4. Miljöbyggnad

Miljöbyggnad is a Swedish environmental certification scheme for buildings. Since its introduction to the Swedish market in 2009, it has become the most prevalent environmental certification scheme in Sweden. The scheme is organised around several main areas – energy and climate, indoor environment, outdoor environment and circularity.

Miljöbyggnad comprises 14 indicators, each setting the requirements at three distinct levels – bronze, silver and gold. In order to qualify for the certification, it is obligatory to fulfil all indicators at least at the minimum level (bronze), which aligns with the standards of typical new construction practices. The silver level is more ambitious, and gold level represents the best available practices. The final grading is decided based on the levels obtained for the specific indicators.

The topic of TC is included in indicators Thermal comfort winter and Thermal comfort summer. The requirements are set in the form of required PPD values for both the winter and summer periods, with management routines for controlling the TC conditions. For the summer period, the possibility for airing is also required. To obtain the highest possible grade (gold), either an occupant survey or TC measurements must be performed. The occupant survey should be conducted earliest after one year of the building operation. Required response rate is at least 75 per cent, and 80 per cent of the occupants should be satisfied with the conditions. In schools, it is the staff that should participate in the survey. Indicator Solar heat load sets limits on maximum solar heat loads in W/m^2 in order to both decrease the overheating risk and need of energy for cooling. The requirements that influence IAQ are set in indicator Phasing out hazardous substances in the form of restrictions on material selections.

3.2.5. Svanen

The Nordic Swan Ecolabel (in Swedish Svanen) is an eco-label used in North European countries (Sweden, Norway, Finland, Denmark and Iceland), in 1989. This eco-label is widely used to certify products and services, but it can also be used for certification of buildings [45]. Svanen offers also a separate version for building renovations, but it is not described in this review.

Svanen includes both obligatory criteria, which must all be fulfilled in order to qualify for certification, and optional criteria awarded with points. In order for a building to be certified, a minimum number of points must be achieved. Certain criteria differ among the countries where the certification is used, reflecting local legislation or requirements.

Aspects related to IAQ are included in a form of restrictions on the choice of materials, chemical and other building products, as well as emissions from the materials used. Many of these requirements are obligatory. TC requirements are included in an obligatory criterion focusing on thermal comfort and overheating. Rooms with the risk of overheating need to be identified and evaluated, and solar protection must be installed in order to fulfil the prescribed criteria for operative temperature. Furthermore, another optional criterion encompasses solar shading and energy efficient cooling. Points are granted for the utilisation of the specified technologies or strategies used to control the indoor temperature, such as external solar shading provided by architectural elements or vegetation, free cooling from a geothermal source, automated night ventilation or other cooling technologies that do not necessitate the installation of mechanical systems. Regarding building envelope quality, an obligatory criterion focusing on airtightness testing is included.

3.3. IAQ and TC criteria in building design and construction systems

In this section, comparison of IAQ and TC criteria included in the certification systems for building design and construction is presented.

3.3.1. Ventilation

Table 6 summarizes the ventilation design requirements and strategies present in the certification systems.

Requirements related to ventilated design are included in BREEAM, LEED and DGNB. These are often specified as a requirement to follow procedures in relevant standards or legislation. CO_2 concentration limits are given by referring to specific standards in DGNB and LEED.

Neither Svanen nor Miljöbyggnad does include any requirements related to ventilation rates or design. Miljöbyggnad only requires having valid OVK (obligatory ventilation control).

3.3.2. Indoor air pollutants

Table 7 shows which systems require to meet specified limit values for certain pollutants.

Almost all systems set limits to at least some pollutants or PM concentrations, LEED being the most detailed. Measurements of NO_x are not required in any of the systems.

Noticeably, LEED is the only system including limits for PM concentrations. DGNB offers extra points when the use of low-emission inkjet printer installed in separate rooms preventing the PM concentration in interiors, however it does not set any other requirements related to PM concentration.

Table 6
Ventilation requirements and strategies present in the certification systems.

	Ventilation rates and design	CO_2 limits
BREEAM	Refers to valid Swedish building code [58] and requirements from Swedish work environment authority (AFS 2020:1) [61]	*Not given*
LEED	Refers to ASHRAE 62.1–2016 [70]	Refers to ASHRAE 62.1–2016, appendix D. [70]
DGNB	Refers to DIN EN 16798–1 [71]	Refers to limit categories in DIN EN 16798–1 [71] (points awarded for max. 800 ppm CO_2 above the outdoor air concentration)
Miljöbyggnad	–	*Not given*
Svanen	–	*Not given*

Pollutants listed in Table 7 are required to be measured during post-construction stage. Further information about assessment of these pollutants follows in chapter 3.3.4.

Svanen does not set any pollutant limits, however, it does include a substantial number of requirements pertaining to the selection of materials. Similar requirements are also included in other certification systems.

Certification systems also include information and guidance on measurements procedures and methodology, e.g. how the sampling should be conducted and what methods should be used to analyse the samples. The systems usually refer to same standards, such as ISO 16000–3 [72], or ISO 16000–6 [73]. For more information about the requirements and methods, we refer to the respective certification manuals.

3.3.3. Thermal comfort and RH

Table 8 summarizes the requirements included in the certification systems related to TC. All of them include aspects related to TC, but the level of detail and chosen approach vary. The TC models included in the table were either mentioned in the manuals or in the standards that manuals refer to.

Most of the certification systems work with both PMV/PPD and adaptive thermal comfort models.

Interestingly, requirement for RH is included only in DGNB. Recent study by Wolkoff [78] confirmed the role of RH in work productivity and especially reduced risk of infection when the RH is between 40 and 60 %. A review by the same author [79] mentions potential synergistic effects between low RH and certain pollutants, such as ozone. Given the high ventilation rates that are needed in densely occupied spaces such as schools, there is a risk for low RH values during heating season even in temperate climates.

Svanen includes requirements related to overheating by setting a maximum number of hours when the set operative temperature is exceeded. DGNB also sets requirements for higher and lower limit of operative temperature, generally in line with EN 16798. Furthermore, DGNB includes detailed requirements for thermal comfort indicators such as draft, radiant temperature asymmetry and floor temperature, all of them specified separately for cooling and heating period. Different number of points is awarded when the design complies with different category as specified in the standard, which could imply that category I requirements creates better IAQ and TC. However, the categories in the standard are related to the level of expectations of the occupants, stating that "a higher level may be selected for occupants with special needs ", such as children or elderly, and giving tighter IAQ and TC requirements (ref to standard). The misuse of these categories as indicators of building quality has been criticised on the above grounds [80].

3.3.4. In-situ IAQ and TC assessment

There are two types of in-situ assessment included in the certification schemes, i.e. post-construction and post-occupancy. Post-construction assessment is usually required right after when the building construction is finished, but before the occupants move in, with some exceptions.

Summary of assessment methods in the certification schemes is included in Table 9. Generally, the systems focus only on post-construction stage, except for Miljöbyggnad. This means that it is the design conditions that are verified, not the operational conditions. The verification methods are not included in the mandatory requirements, with the exception of Miljöbyggnad's requirement for obligatory ventilation control.

In Sweden, a ventilation control called obligatory ventilation control (in Swedish *obligatorisk ventilationskontroll – OVK)* is required after the building construction is finished, and then regularly in set intervals during building operation (once in 3 years for school buildings). This control comprises the general control of ventilation system functionality as well as measurements of air flow and their conformity with the intended design values. The results should be always submitted to

Table 7
Requirements for pollutants and particulate matter.

	Formaldehyde/ VOC/ TVOC	Radon	Ozone	CO	NO_x	PM10	PM2.5
BREEAM	yes	yes	–	–	–	–	–
LEED	yes	–	yes	yes	–	yes	yes
DGNB	yes	–	–	–	–	–	–
Miljöbyggnad	–	yes	–	–	–	–	–
Svanen	–	–	–	–	–	–	–

Table 8
Thermal comfort assessment methods and indicators.

	Thermal comfort standards and guidelines	Thermal comfort models	Temperature requirements	RH level values
BREEAM	SS-EN ISO 7730:2006 The Swedish Public Health Agency's general guidelines on indoor temperatures [60]	PMV/PPD Adaptive model*	As per [60]: maximum operative temperature 24 °C	–
LEED	ASHRAE 55–2017 [74] or local equivalent	PMV Adaptive model	As per referred standard	–
DGNB	DIN EN 16798–1 [71], DIN EN ISO 7730 [75], DIN 4108–2 [76]	PMV/PPD Adaptive model	As per referred standard	RH heating period: ≥30 % over at least 95 % of the operating hours RH cooling period: Absolute humidity <12g/kg
Miljöbyggnad	-	PPD	–	–
Svanen	–	–	Operative temperature >26 °C max 100 h per year >27 °C max 25 h per year	–

* Even though it is not mentioned in the technical manual, BREEAM also accepts the use of adaptive model for naturally ventilated buildings (referring to CIBSE TM52: The limits of thermal comfort: Avoiding overheating in European buildings), as noted in BREEAM Knowledge Base [77].

Table 9
Assessment and verification methods used in construction systems.

	Measurements	Occupant surveys
BREEAM	IAQ – post-construction (TVOC, formaldehyde, radon)	Post-occupancy
LEED	IAQ – post-construction (PM, CO, ozone, TVOC*) + CO_2 monitoring	–
DGNB	IAQ – post-construction (TVOC, formaldehyde)	–
Miljöbyggnad	TC – post-occupancy Air flow measurements (Obligatory ventilation control)	TC – post-occupancy
Svanen	–	–

Notes:
* LEED requires additional measurements of specific VOCs in case the limit TVOC values are exceeded in order to identify the source of the exceedance. For details, we refer to the certification manual.

municipal building committee, but conduction of this obligatory control is also required by Miljöbyggnad.

All certification systems, except for Svanen, include requirement for some form of measurements to be conducted in post-construction phase before the occupants move into the building. These measurements are mostly related to VOC or TVOC concentrations. LEED includes requirements for continuous CO_2 monitoring within occupied spaces as one of the optional strategies. Monitors should be able to alert the building automation system when the CO_2 limit is exceeded. BREEAM requires post-occupancy evaluation survey one year after the building was set in operation. Miljöbyggnad requires either occupant survey that meets prescribed occupant satisfaction levels, or post-occupancy thermal comfort measurements in order to receive the highest possible rating (gold) in indicators related to thermal comfort.

3.4. *Certification systems focusing on building operation*

In this part of the analysis, the certification systems used for buildings in operation are described. Systems for buildings in operation can be applied to buildings which are already in use for a specified time. Previous certification of the building is usually not required.

3.4.1. *BREEAM In-Use*

BREEAM In-Use is divided into two parts – asset performance and management performance. Asset performance can be used for not yet occupied building, while evaluation using the management performance requires at least 12 months of building operation prior to the start of the assessment.

Asset performance includes the topics focusing on IAQ and TC in the chapter Health and Wellbeing, similar to BREEAM New Construction. The evaluation criteria in Asset performance include ability to control the comfort by users, location of ventilation system intakes and exhaust to minimise entry of pollutants and presence and function of CO_2 and CO sensors. In management performance the evaluation criteria are more extensive. In its corresponding chapter Health and Wellbeing, it includes thermal comfort monitoring via occupant surveys and detailed measurements and analysis method in line with international standards using adaptive comfort models or analytic PMV/PPD models. For adaptive model, BREEAM In-Use allows use of both the ASHRAE and the European standards, alternatively any other local standards that includes similar requirements. Procedures for addressing the issues and feedback related to TC measurements and surveys should be in place. For indoor air quality the criteria are somewhat different, with requirements for management processes, policies and procedures to help maintain good level of IAQ, and measurements of air quality parameters and pollutants. These post-occupancy measurements should include CO_2 and at least two pollutants from the given list which includes PM, TVOC, formaldehyde, CO, NOx or radon. Finally, in a separate chapter named 'Management', the listed evaluation criteria are tightly related to IAQ and TC, e.g. provision of building user guide including building services and access to building occupant controls, user feedback and communication processes, and maintenance policies and procedures for building services.

3.4.2. *LEED O+M*

LEED O+M (Operations and maintenance) is intended to be applied to buildings which are at least a year in operation. This certification system offer certification for existing buildings, or for an existing interior (commercial, retail or hospitality), which is part of an existing building. Here, only the option for existing buildings is described. The rewarding system is similar to the one used for buildings in construction. The certification is valid for three years and after this period recertification is required.

The majority of the credits related to IAQ are mandatory. These include tobacco smoke control, maintenance of ventilation systems and IAQ assessment. The latter entails conducting occupant survey and IAQ measurements. Post-occupancy measurements of CO_2 and TVOC is required. Projects are encouraged to conduct measurements for more pollutants, including CO, O_3, PM2.5 and several types of VOCs such as formaldehyde, benzene, acetaldehyde and more. Including measurements of two more pollutants from the list can results in obtaining additional points. Great focus is put on cleaning and cleaning policy, which is a part of both required and optional credits.

3.4.3. DGNB Buildings in Use

The first version of DGNB for buildings in operation was introduced in 2016. Unlike the DGNB for new constructions, no minimum performance index per topic is required. Furthermore, the system does not distinguish between different building types.

In DGNB the building must have been in operation for at least one year at the time of the certification. Previous certification of new building is not necessary. Every three years the criteria must be checked again, including submission of necessary evidence. The criteria on indoor comfort include data collection via short-term measurements during extreme conditions or long-term continuous measurements and occupant surveys, analysis and action, i.e. optimisation according to findings from the analysis. Measured parameters should at least include indoor temperature, indoor humidity and CO_2 concentration. Bonus points can be awarded when measurements of certain TC and IAQ parameters (draught, radiation asymmetry, pollutants such as VOC, SVOC or formaldehyde) are conducted to assess the data from surveys, complaint management or from building inspections. Other criteria include management procedures, such as guidelines for technical monitoring, hazard classification of air quality based on site characteristics, implementation of complaint management and communication and interaction with building users.

3.4.4. Miljobyggnad iDrift

Miljöbyggnad iDrift *(in use)* includes five different assessment areas and a total of 15 indicators. Each indicator typically comprises both mandatory and optional criteria, for which points are awarded. Unlike the other systems included in this review, the building must be in operation for at least three years to qualify for the certification. The reward system is slightly different to Miljöbyggnad for new construction. Final grade (bronze, silver or gold) is based on the total number of points achieved. It is required to annually confirm that the requirements set out in the criteria submitted during certification process are still fulfilled. The recertification process should be initiated no later than five years after the initial certification.

The topics relevant to the IAQ and TC in building operation process are dispersed within several indicators. The criteria include focus on HVAC system and maintenance, building operation and control. Ventilation system operation and maintenance are also covered. TC related aspects are also included, such as control measurements of indoor temperature, requirements for thermal comfort occupant surveys and solar shading. Communication between building users and management, requirement for maintenance plan as well as requirements related to cleaning are also covered.

3.4.5. Assessment and verification methods

Table 10 summarizes the assessment methods used in the certification systems for buildings in operation. Unlike the methods summarized in Table 9, these assessment methods are always conducted during post-occupancy stage, which means, that the actual operational conditions are verified.

As apparent from the table, all the reviewed systems include multitudes of verification methods. Some of the certification systems requires both IAQ and TC measurements, as well as surveys focusing on both topics. IAQ measurements mostly include measurements of VOC/TVOC or CO_2, however, other pollutants, such as PM, are rarely included.

Miljöbyggnad does not include requirements for IAQ measurements, instead it focuses only on verification of thermal conditions using both measurements and surveys. Additionally, it again emphasizes the requirements for conducting the obligatory ventilation control, as required by the Swedish National Board of Housing, Building and Planning.

4. Discussion

This review has demonstrated that there are differences between certification systems, both in terms of their scope and the level of detail they encompass. Some systems cover a significant number of crucial aspects that are essential for establishing optimal TC and IAQ, while others focus only on a subset of these aspects. Table 11 summarizes the main advantages and disadvantages identified in this review, which are further discussed in this section.

There is also a clear difference in the scope of the systems focusing on design and construction and systems focusing on buildings in operation, which is apparent also from their titles. Generally, design and construction systems do not cover the specifics of the post-occupancy stage, such as building management and operation. Furthermore, these systems do not encompass the verification methods conducted during the post-occupancy stage. Therefore, it cannot be assumed that buildings awarded these types of certificates will necessarily provide high-quality TC and IAQ conditions. These buildings might have fulfilled certain assumptions and design preconditions potentially leading to good TC and IAQ conditions, however, the certification systems rarely include tools and strategies needed to verify that conditions are fulfilled during post-occupancy. The same issue is also extensively criticised in [9]. It is well documented that building occupants and building operation itself significantly influences the conditions in the building during post-occupancy [32,81]. Furthermore, not all certification systems include the requirements related to TC and IAQ in their mandatory parts, or, in certain cases, only the most fundamental criteria are required as a prerequisite for certification. This can result in awarding a certificate without meeting any or only very basic requirements pertinent to these topics. This is particularly important for the case of school buildings, where specific air quality parameters have been found to be

Table 10
Assessment and verification methods included in the systems used for buildings in operation.

	Measurements	Occupant surveys
BREEAM In-Use	IAQ measurements (CO_2 + at least two other pollutants such as PM, TVOC, formaldehyde, CO, NOx, radon)	TC survey
	TC measurements	IAQ perception survey
LEED O+M	IAQ measurements (CO_2 and TVOC)	Occupant satisfaction survey
DGNB In-Use	TC measurements	Occupant satisfaction survey
	IAQ measurements (only VOCs)	
Miljöbyggnad iDrift	TC measurements	
	Obligatory ventilation control (OVK)	IEQ occupant feedback TC survey for winter and summer

Table 11
Advantages and disadvantages of the analysed certification systems.

Advantages	Disadvantages
• Third party supervision and assessment	• Increased resources and costs
• Wide range of IAQ and TC assessment methods	• Lack of incentives (especially for public educational buildings
• Higher and wider requirements compared to national legislations and standards	• Focus limited only on particular stage of building life cycle (design/ construction vs. operation)
• Focus on management and communication between building users and operators	• Lack of specific focus on certain typical IAQ and TC issues and challenges in schools

significant, e.g. PM, and the main occupants are rather sensitive. For the schemes to be able to lead to better IAQ and TC in schools, it would therefore be necessary to include these in the criteria and make them mandatory.

On the other hand, certification systems for buildings in operation typically cover operational and management aspects which are essential for maintaining high-quality indoor conditions. These include management strategies, communication between occupants and building management, and verification methods in a form of regular measurements and occupant surveys. Therefore, the application of certification systems for building in operation can be considered as superior to those intended for building design and construction in achieving high quality TC and IAQ conditions. This statement is also valid for school buildings, as the criteria included in the certification systems, especially the assessment methods, are essential in the process of identification of potential IAQ and TC issues and their remediation.

As emphasized throughout this article, schools accommodate a particularly sensitive group of occupants with specific needs and increased health risks when being exposed to inadequate IAQ and TC conditions. Generally, the analysed certification systems do not include many specific requirements for schools, nor do they put increased emphasis on IAQ and TC topics. Some of the systems assign different importance to different topics in a form of number of points available. LEED has also a special version for schools, but the difference in the studied topic is minimal compared to the version for new constructions. Increased focus on ventilation related issues and TC would be beneficial. For example, the requirements for TC could better reflect the discussed differences in TC perceptions and needs. However, even though this topic is heavily discussed in scientific literature, the consensus has still not been achieved, and no standards distinguish yet between different age group when providing guidelines on TC.

To lift some positive aspects, the use of certification systems offers several advantages. One of the most significant benefits is the supervision and assessment provided by a third party. In the context of standard building practices, fulfilment of all requirements is not always a subject of verification. The certification process usually entails comprehensive scrutiny of all submitted documentation, on-site verification of compliance, and periodic data submission or recertification after designated interval. These procedures should guarantee that the criteria required for the certification are met even during the course of building operation. Furthermore, the range of verification methods included in certification systems for operational buildings offers additional advantages. When combined with effective management routines, these should result in continuous enhancements in building performance and prompt responses to operational deficiencies or occupant feedback identified through measurements or surveys.

The implementation of certification systems may be perceived as a disadvantage in cases where increased costs and resources are concerned, particularly in the context of educational buildings financed from the state budget. However, another factor making the certification systems attractive is the potential to enhance the market value and attractiveness of the building. A literature review examining the effect of building certification on cash flow and values of commercial properties found that certification increases the rental incomes, sales prices, and occupancy, and reduces the operating costs [82]. Though being an important factor for commercial buildings, this is typically not relevant for school buildings, as they are in many cases financed by public sector. Therefore, more incentives for certification of schools are needed. Emphasizing the special requirements reflecting the school children's specific needs could act as one of them.

In contrast to the national requirements, certification systems, especially those focusing on buildings in operation, comprise a range of assessment methods, including IAQ and TC related measurements and occupants' surveys. While measurements provide objective information about the actual conditions in the building, surveys collect building occupants' subjective opinions and perceptions of the indoor environment. In schools, there are typically two distinct categories of occupants – pupils and adult staff. The two groups may have different expectations and perception of the conditions indoors [13]. Typically, the first group – pupils – is the larger of the two, but the second group – staff including teachers – usually plays an active role in forming the indoor environment by opening the windows, changing the setting of thermostats etc. Therefore, the environmental conditions of classrooms are typically the result of the teachers' preferences [83].

Miljöbyggnad instructions mention that the surveys are usually to be answered by staff, and not by the pupils or students. However, neglecting the pupils' opinion may result in providing inappropriate IAQ and TC conditions. Conducting the occupant surveys with children is challenging and, in the case of the youngest children not even appropriate due to their not yet developed cognitive abilities [84]. However, the same paper suggests that children from the age 8 onward can be surveyed. This means that the majority of the primary school pupils could participate in the occupant survey when the questions are appropriately formulated with respect to the targeted age group. Instructions on surveys in all certification systems should therefore encourage to include the children and students in the surveys to obtain information about their perceptions and preferences and to be able to adjust the IAQ and TC accordingly.

It is also important to acknowledge that perception of IAQ and TC can also be attributed to other factors, as discussed in [85]. In the case of schools, surveys may pose another risk of limited comprehension of the survey questions among the youngest children, as discussed above. Therefore, surveys should be complemented with physical measurements of selected IAQ and TC indicators. Verification of the TC and IAQ conditions is a necessary step in the process of providing high-quality IEQ, especially in such densely occupied environment. Even though there are legislative requirements related to ventilation rates (Table 1), it is not a guarantee that these are fulfilled in practice. This is evidenced by a study investigating TC and IAQ in 45 primary school classrooms in Gothenburg, which revealed that two-thirds of the investigated classrooms, even those ventilated mechanically, did not comply with the Swedish ventilation requirements [38].

As apparent from Table 8, PPD/PMV models are heavily used in the design phase with either modelled or assumed environmental conditions and personal factors as input variables. These are usually not verified with measured environmental conditions and observed personal factors. One exception is BREEAM in Use, which includes the requirements for calculations of PMV/PPD indices based on physical thermal comfort measurements.

The strong focus on source elimination strategies in the form of use of low-emitting materials and products can also be perceived as an advantage, as the focus on pollutants is generally low in national legislations. Source elimination strategy is an effective way leading to lower indoor air pollutants concentrations. On the other hand, some strategies suggested to improve the IAQ may not be appropriate in school environments, such as to increase ventilation rate by certain percentage above the minimum required rate. Potential benefit of such measure in schools, in which the necessary ventilation volumes are already large due to high occupancy, is doubtful. Such measure can also lead to low RH, especially during heating seasons in the Nordic climate. Furthermore, the impact on the energy use would also be negative. Another questionable strategy is to temporarily increase ventilation rates during the post-construction or early post-occupancy stage. This procedure is often used to ventilate new building where high levels of VOCs and other pollutants are expected. However, as addressed in a study by Domhagen [86], research shows inconsistent results regarding the impact of increased ventilation on the emission rates from materials, so this strategy can more probably lead to waste of energy. Instead, focus could be put on source elimination.

Some certification systems entail extensive IAQ measurements during building operation or continuous monitoring of CO_2 concentrations. The second option is relatively low-cost solution used for monitoring IAQ, as CO_2 is in many cases correlated to other pollutants [38]. It is beneficial when the IAQ measurements are conducted during different seasons, as the behaviour of occupants differs based on outdoor weather conditions [87]. However, the attention paid to PM, which were identified as one of the major contributors to indoor pollution in schools [3], is quite limited and even almost omitted in some of the investigated certification systems.

Other aspect influencing the IAQ and TC conditions in the buildings, but being overlooked in most of the certification systems, is the design of the building envelope from IAQ and TC perspectives. Some systems include more or less detailed site assessment including solar exposure, average monthly temperatures or outdoor pollution, but the focus on building envelope is mostly only from an energy point of view. For instance, the certification systems could include more criteria encouraging the design team to explore the opportunities and options of adjusting the building form, shape, envelope and also systems to minimize the risk of overheating and ingress of pollutants. Such analyses could support the design team to always choose the most appropriate design aspects and strategies for the specific case.

Finally, the current state of the indoor environment in school buildings is likely not a sole problem of deficient design. It is presumably a combination of more aspects originating from different building lifecycle stages, including design, construction, operation, maintenance and eventually also renovation. Therefore, in order to provide good IAQ and TC, it is important to put focus on all these stages. Separate certification focusing on one particular stage can be useful in laying foundations or improving the conditions, but it is essential to continuously work on IAQ and TC throughout all the stages to obtain the best results.

5. Conclusion

The popularity of building certification systems has increased rapidly in the recent years. The application of such systems has advanced from offices to other types of buildings, including schools. These types of buildings often suffer from unsatisfactory IEQ conditions that fall short of even the national requirements, as evidenced by a number of studies and literature reviews. Therefore, this critical review aimed to contribute with critical perspectives on whether and how building certification systems can be used for promoting better TC and IAQ in school buildings.

The selected certification systems (BREEAM, LEED, DGNB, Miljöbyggnad and Svanen) which are used in the countries of Northern Europe were subjected to an analysis with the intention of facilitating a comparison of their respective scope and criteria.

In general, it can be concluded that the certification systems can be successfully implemented with the intention of providing good TC and IAQ conditions in schools. One of the most robust strategies is the system of supervision which is an essential part of each of these systems. Compared to national TC and IAQ requirements, the certification systems include wider range of requirements. However, the systems for building design and construction generally miss the necessary verification tools, such as occupant surveys and measurements of IAQ and TC aspects during post-occupancy stage. Consequently, the issuance of such type of certificate should not be perceived as a guarantee for high-quality IAQ and TC. It can be rather viewed as a favourable prerequisite for that. In contrast, the systems intended for buildings in operation include these verification methods as well as management and operational practices which are essential for providing good TC and IAQ conditions and therefore can be considered as much stronger tools.

Besides that, the investigated systems differ in the range of covered aspects related to IAQ and TC. Even though some of them offer much wider range of criteria than others, each of the systems cover at least a few of the major TC and IAQ issues typical for school buildings and the requirements go beyond those set in national legislations. Therefore, there is a potential that implementation of certification systems can help avoiding repeating some typical deficiencies in TC and IAQ of school buildings. However, some of the important aspects would deserve greater attention, such as focus on building envelope design from the IAQ and TC perspective, and focus on PM concentration, which is one of the most significant pollutants in school buildings.

CRediT authorship contribution statement

Blanka Cabovská: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Despoina Teli:** Writing – review & editing. **Lars Ekberg:** Writing – review & editing, Resources.

Declaration of competing interest

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

Acknowledgment

This work was funded by the Department of Architecture and Civil Engineering, Chalmers.

Data availability

Data will be made available on request.

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