Multicriteria Design: Optimizing Thermal, Acoustic, and Visual Comfort and Indoor Air Quality in Classrooms

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Abstract Indoor Environmental Quality (IEQ) is a crucial for ensuring comfortable and healthy indoor spaces, and it is influenced by four primary factors: thermal comfort, acoustic comfort, visual comfort, and air quality. These aspects have a combined influence on the overall perception of comfort, and therefore, need to be assessed with a holistic approach. This chapter presents design strategies that would generate the indoor environmental conditions needed to ensure IEQ in school classrooms in the Global South. First, the design strategies are identified and classified for each aspect of IEQ based on a literature review. Then they are organized, and conflicting design strategies are identified. Finally, a design workflow for the incorporation of passive design strategies in school classrooms is presented.

Keywords Indoor environmental quality · Interactions · Adaptive comfort · Indoor air quality · Acoustic comfort · Visual comfort · School classroom

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1 Introduction

Indoor environmental quality is a broad concept that includes thermal, visual, and acoustic comfort as well as indoor air quality. The REVA guidebook [1] proposes that the perception of comfort is dependent on the building's use, outdoor conditions, building design, and the services in place. Recent research has also shown that the personal characteristics of occupants, as well as previous experiences, expectations, and interaction with the building, play a role in the perception of comfort [2].

The quality of indoor environment has well-known impacts on occupants' health and well-being. This is especially relevant in school classrooms where children spend between 799 (elementary school) and 913 hours per year (high school) in OECD countries [3]. The exposure to indoor environment at school as well as their experience at home will shape their comfort expectations for the future.

On the other hand, buildings need to avoid overreliance on energy-consuming strategies to ensure the quality of indoor environment [4]. This is especially true in low-income countries or in buildings serving vulnerable populations. Therefore, there is a need for low-tech solutions that focus on indoor environment quality and energy efficiency. School buildings also have the constraints of low maintenance and operational budgets, and since schools are needed in remote, sometimes inaccessible areas, designers need to consider these constraints.

Passive design proposes strategies that will provide a healthy environment with little to no energy demand. There are many passive design strategies adapted to cool or hot spaces, some to improve light conditions through the use of daylight, some to provide air renewals, and a few on acoustic comfort.

However, there is a lack of knowledge on the impact of these passive design strategies on overall comfort, as well as the effect these strategies have on thermal, visual, and acoustic comfort and indoor air quality. Therefore, this review aims at developing a classification scheme with a holistic multicriteria perspective.

2 Methodology

The research methodology involves two main phases. The first phase is a systematic review of indexed articles and books that present passive design strategies related to thermal, acoustic, and visual comfort along with air quality in educational settings. These publications will be reviewed to retrieve the design strategies used in school classroom design that have a direct impact on IEQ. The second phase will be the classification and cross-examination of the strategies identified to find co-occurrences and how these would interact.

The literature review was limited to the last 20 years and considered thermal, acoustic, and visual comfort, or indoor air quality, related to design strategies applicable to classrooms. The search only considered classrooms as these have specific conditions related to size, occupancy, and period of use, that differentiate them from

Table 1 Keywords used

	Topic	English keyword
1	School classrooms	School building; educational institution; classroom
2	Passive design strategies	Passive design; passive strategy; bioclimatic design; bioclimatic architecture; bioclimatic construction; passive measures; passive system; Architectonic design
3	Indoor environmental quality	Indoor environmental quality; IEQ; environmental ergonomics
4	Thermal comfort	Thermal comfort; thermal sensation; adaptative comfort
5	Acoustic comfort	Acoustic comfort; acoustic design
6	Visual comfort	Visual comfort; light comfort; lighting; natural light
7	Indoor air quality	Indoor air quality; IAQ; outdoor air quality

other buildings. The Scopus database was used to conduct the search. The keywords used are listed in Table 1. The search was defined to include at least one keyword referring to topics 1 and 2, and at least one keyword for topics 3–7.

The selection of papers was made in two steps. First, duplicates were consolidated in the database, then the title and abstract were read to confirm the relevance of the paper for the objective of the review. Papers that were only changing values of the design parameters but not proposing passive design strategies, those that did not consider passive design strategies, were too broad or narrow in scope, or were misclassified by the search engine, were excluded from the review.

In the following step, relevant papers were read and analyzed to extract and identify passive or low-energy consuming design guidelines and architectural solutions, that will provide optimal indoor environmental conditions in classrooms.

3 Results

The review made on the Scopus platform identified 87 documents published between 2012 and 2022. The availability of the authors of 84 articles was established, from all available papers, where 4 were excluded because they were not related to the general research topic; 20 did not study school-level buildings, 4 presented a refurbishment, and 38 presented a case study without passive design strategies. After this step, 15 papers were selected and summarized in Table 2.

All 15 of the reviewed articles included design strategies to improve daylighting and thermal comfort. However, only four of them addressed ventilation, and these primarily focused on heat removal rather than indoor air quality. Additionally, only one article considered acoustic comfort when evaluating the design of a Kinetic adaptive façade [5]. The results of the review are consistent with the idea that passive design aims at improving thermal comfort, while the relevance of the visual aspect in schools makes it relevant to also consider this as part of IEQ. A lack of strategies for indoor air quality and acoustic comfort is identified. This could be related to the predominant use of mechanical ventilation in North America, and the normative requirements for window-sizing in Europe. Acoustic comfort has been a specialist issue, where architects seek expert advice once the initial draft of the architecture is ready.

3.1 Multicriteria Design Recommendations for Comfortable Classrooms or How to Design a Comfortable Classroom

IEQ-related design strategies will have different consequences for each of the four aspects: acoustic, visual, and thermal comfort, as well as indoor air quality. Therefore, the strategies will be presented/classified by their position in the room.

3.1.1 Climate

Climate is of foremost relevance when designing low-tech and low-energy buildings. In the current climate emergency, future climate scenarios should be considered, as schools tend to have a long lifespan. Climate change will affect heating and cooling loads and could also have an impact on rainfall patterns and sky coverage during the year.

Topography, waterbodies, urban heat islands, and vegetation should also be considered as they will characterize a microclimate. This microclimate can also be used in the design to control and change the conditions around the building.

Heating and cooling loads are dependent on the local climate. Tools such as cooling degree days and heating degree days can be used as a first step to assess the climatic conditions but should be complemented with information on pluviometry, daily temperature changes, solar radiation, and sun paths. Humidity, pluviometry, and wind will also affect thermal comfort.

Outside noise is also considered part of the microclimate. Noise sources such as roads, airplane routes, and others should be identified as the building envelope's design needs to be adapted to them.

Wind direction and speed during the year will be especially relevant for design and the use of natural ventilation. Once again microclimate factors such as tall buildings, waterbodies, trees, and others that could affect wind direction and speed need to be considered.

The design incorporating daylighting should consider sky conditions and daylight hours at the location [6]. Tall buildings and other elements that could affect the

Table 2 Design strategies proposed in the identified studies

Ref.		Country	Climate	Classroom type	IEQ aspect(s)	Strategies
1	[6]	Iquique, Santiago and Coyhaique, Chile	BSk, Csa, Cfc	School classroom	Daylighting	–Light shelves –Light shelves and lower blinds –Upper blinds –Light shelf and skylight
2	[7]	Iquique, Santiago and Coyhaique, Chile	BSk, Csa, Cfc	School classroom	Daylighting, Thermal comfort	–Orientation –Infiltration –Glazing area per square meter –Type of glazing –Enhanced walls and roof insulation
3	[8]	Seoul, Korea	Dwa	School building	Daylighting	–Dynamic exterior blinds –Automated artificial lighting –Heat Exchanger (HE)
4	[9]	Taiwan	Cfa	School building	Natural ventilation, Daylight, Avoidance of solar heat gains	–Green roof –Exterior shades –Greenery outside windows –Operable windows and electric overhead fans –Enhanced walls and roof insulation
5	[10]	Tehran, Iran	Csa	School building	Thermal comfort	–Orientation –Wall and roof insulation –Night-time natural ventilation –All-day natural ventilation –Fins and overhangs –Thermal mass
6	[11]	Auckland, New Zealand	Cfb	School building	Energy consumption	–Area to volume ratio –Window area to building volume

(continued)

Table 2 (continued)

Ref.		Country	Climate	Classroom type	IEQ aspect(s)	Strategies
7	[12]	Tianjin, China	Dwa	School building	Heating and cooling demand, Thermal comfort, Daylight	–Orientation –Room depth –Corridor depth and configuration –Window-to-wall ratio –Glazing material –Shading types
8	[13]	Sharjah, UAE	BWh	School building	Thermal comfort, Ventilation	–Open and closed courtyard
9	[14]	Tehran, Iran	Csa	School classroom	Heating and cooling, Daylighting	–Overhang –Blinds –Light shelf
10	[15]	Madurai, India	Aw	University classroom	Thermal comfort, Ventilation	–Vertical and horizontal shading devices
11	[16]	Seoul, Korea	Dwa	School classroom	Daylighting	–Vertical and horizontal shading devices –Outdoor horizontal fins
12	[17]	Kuala Lumpur, Malaysia	Af	School building	Natural ventilation, Daylighting	–Ventilation blocks
13	[18]	Hebron, Palestine	Csa	School classroom	Thermal comfort	–Solar chimney –Solar wall –Underground duct
14	[5]	Ho Chi Minh City, Vietnam	Aw	School classroom	Acoustic comfort	–Kinetic adaptive façade
15	[19]	Biskra, Algeria	BWh	School classroom	Thermal comfort, Daylight	–Window-to- wall ratio –Glazing –Vertical and horizontal shading

availability of light should be considered. Visual comfort also includes views, which should be studied to provide, if possible, views of nature.

Once the climate and site are characterized, passive design strategies can be proposed. Here, an analysis per element is proposed in the classroom envelope setup. The aspects of each element that affect acoustic, visual, and thermal comfort as well as indoor air quality and their interactions are described.

3.1.2 Walls

Walls are the biggest part of the envelope in classrooms. From the inside, these are always visible to students and act as the background for the visual field. From the outside, they are the protective layer, that is in direct contact with the climate.

Wall Insulation

The building's envelope comprises walls, windows, doors, the floor, and the roof. The materials used in walls need to be adapted to the outdoor climate. Choosing proper insulation materials is of the utmost relevance. It is relevant to note that thermal insulation materials can also double as acoustic insulation materials. Each country has its own insulation requirements, but the general approach should be to lower the need for heating and cooling as this will lower operation and maintenance costs.

For acoustic insulation, the rationale is to identify noise sources and design the envelope so that each classroom has a similar level of outdoor noise insulation. Airborne sound insulation of the façade should be used as an indicator for outdoor-facing walls and airborne sound insulation between spaces for indoor-facing ones [20].

Air infiltration should also be considered. Infiltration is the uncontrollable movement of air through cracks and small holes in the envelope. It can also generate interstitial condensation in the walls.

Thermal Mass

Thermal mass can store thermal energy and can be used to lower temperature variation during the day or to store heat during the day. Combined with good ventilation that removes heat through night-time ventilation, this strategy can be used in hot climates. Thermal mass, because of its composition also provides airborne sound insulation.

Finishes

The color, materials, and reflectance will affect the perception of light. The reflectance of walls will affect the perception of glare inside the classroom [21]. It is recommended to use light colors to better distribute luminance by inter-reflection, and avoid high contrast between the window area and the wall.

Color, although not clear, has been linked with thermal perception [22] in experimental settings, where, warm colors make people feel warmer and cold colors colder. There is no clarity about the saturation needed to observe this, or if it would affect thermal perception in a classroom.

The materials used for finishes in classrooms will affect how the voice of the teacher is perceived. It is recommended to include absorbent panels on walls to improve the acoustic quality of the space [23] as a complement to ceiling acoustic absorption.

3.1.3 Windows

Climate will be the first parameter under study when designing windows in a classroom. Outdoor temperatures and wind direction, sky conditions, daytime hours, and pluviometry, should be known in detail for the location of the classroom.

Windows in classrooms are designed mainly to provide daylight as well as providing natural ventilation. In the Global South, most classrooms rely on natural ventilation to provide fresh air [24] to lower operational and maintenance costs. It is also relevant that these systems can work when electricity is scarce or not reliable, making the buildings resilient. The design of windows will also have an impact on thermal comfort and acoustic comfort which should be considered.

Window Orientation

The preferred position of the window in the literature is the façade that does not receive direct sunlight. In the case of the southern hemisphere, this is the south-facing façade. This preference is based on the idea that avoiding direct sunlight will diminish glare and patches of direct solar radiation on the body of the students which would affect their thermal perception. When considering this issue, it is relevant to study not only the orientation of the window, but also if reflective objects on the outside could redirect sunlight into the classroom and if there are obstructing elements that will diminish direct and indirect sunlight. The same principles apply when designing for natural ventilation. Most of the time, the orientation of the building is given beforehand, and the design of the building needs to respond to the constraints of a given site.

It is also relevant to consider that noise could enter the building through the windows. Therefore, windows facing noisy streets or courtyards should be avoided. In this case, one recommendation could be to separate ventilation from lighting.

As stated by Montazami et al. [25], outdoor noise can be detrimental to Indoor Air Quality, because the noise would be more disruptive for the teaching than poor air quality, skewing decision-making toward eliminating noise. When pondering Indoor Air Quality against thermal comfort, research shows that air quality will be neglected in favor of avoiding temperature loss [24].

Ventilation Patterns

Ventilation is the main strategy to provide good indoor air quality by removing contaminants produced inside the classroom. Natural ventilation is the preferred option as it is low-tech, does not require energy, and its maintenance is low. Depending on the characteristics of the climate, different strategies can be used. Ventilation will also remove heat if outdoor air is cooler than indoor air. If the temperature difference is above 2°C, air movement could provide a cooling effect.

Single-side ventilation is the most commonly used option in classrooms, although it is not the most effective strategy. It is reliant on wind pressures on the façade and the stack effect. Due to the high occupancy of classrooms, a more effective ventilation strategy should be preferred.

Cross-ventilation is when two or more windows on different walls are open. The difference in pressure between both sides of the building will cause the removal of indoor air. This strategy will work in narrow buildings, where the distance between windows is less than 5 times the height of the room and less than 15 m. This strategy is dependent on window size and location.

Stack or convective ventilation uses the stratification caused by the air temperature. As the air warms, it becomes less dense and rises. The rising air is removed and replaced by air entering at a lower temperature from outside. This strategy requires openings at the bottom and top of the building or roof operable windows. The main advantage of this strategy is that it is independent of wind speed, therefore, it can be used in climates with low wind velocity or when it is not possible to face prevailing winds.

Solar chimneys are another ventilation strategy comprising three fundamental parts: a solar energy collection area at the top of the chimney, the main ventilation shaft, and air intake and exhaust ducts. Heating the air with solar energy at the top of the chimney increases the temperature difference between the incoming and outgoing air, which in turn increases the velocity at which it moves within the chimney.

Window Size

Window geometry in classrooms is usually defined by the need to provide daylight. Windows should provide natural light, as uniformly as possible to the whole classroom during most of the time in use. Design strategies such as light shelves [14] and high windows could improve light distribution when used correctly.

When deciding the size of the window, glare probability should also be assessed as too much light can be just as detrimental as a lack thereof.

To counteract the possibility of glare, solar protection should be designed. Indoor curtains should not be an afterthought, and if possible, should be specified at the design stage. Indoor and outdoor blinds and louvers could also be designed when needed [15, 16, 19].

To ensure proper ventilation for the removal of indoor pollutants, the size of the operable windows should be considered. It is relevant to consider the orientation of the window and the type of opening as this will determine the efficiency of the system. As stated before, it is possible to uncouple ventilation from lighting if needed as noise from the outside can affect the learning process [26].

Window Materials

The design of windows should consider at least three main aspects: frame, pane, and opening. The frame material and design will affect the thermal conductivity of the window, noise transmission to the frame, air permeability, and the area that is transparent. Frame design varies enormously depending on the available manufacturers and designs; therefore, this will not be further discussed. It is advised to thoroughly review the specifications of several options considering the aforementioned aspects.

Window panes are usually glass. Thermal transmission should be the first aspect to consider using the local regulations and requirements, to better adapt to the climate. Single pane glass will have a transmittance between 5.4 and 5.85 $W/(m^2K)$, and a double pane 1.8 and 3.4 $W/(m^2K)$, depending on the design of the pane and glass. The solar heat gain coefficient (SHGC) is the fraction of solar radiation admitted through a window. The lower the SHGC, the less solar heat it transmits, and the greater its shading ability.

Pane design will also affect acoustic performance. Double-pane glass will have better sound insulation than single-pane. The separation between the panes will also improve sound insulation.

Visible transmittance (VT) is a fraction of the visible spectrum of sunlight that is transmitted through glazing and is expressed as a number between 0 and 1. Glass with a lower VT can be used to reduce glare. Double glazing will have a lower VT than single glazing, but there are other, more effective strategies to control this.

The opening of the window will determine air tightness and ventilation potential. Sliding windows tend to be less airtight than hung and pivoting windows, although this is heavily dependent on the design and quality of the manufacturing process. Ventilation potential should be considered as it will define the available area for natural ventilation. Hung and pivoting windows will account for more ventilation area than sliding windows.

Outside View

Although teachers perceive an outside view as distracting for students, it is also relevant to consider the visual aspect of windows when defining their size. The benefits of visual connection to the outside have been proven, especially when a view of nature is available [27].

A view of nature has been linked to children's well-being [28], while previous studies have found a link between a pleasant view that includes vegetation and better learning outcomes [29]. The current daylighting standard, EN 17037 2018, includes outside views as an indicator that should consider a clear vision outside, a horizontal view from a certain position in the room, and a view that considers more than one layer of information. Kent and Schiavon [27] argue that since nature has a "stronger association with psychological restoration and positive affect", this type of outside view surpasses the minimum requirement, without the need to include more layers of information.

For classrooms, it is relevant to consider the height of the window from the perspective of students sitting and teachers. Younger students will require different windowsill heights than older ones. All students in the classroom should have access to an outside view from their location. Another aspect that interrupts the view is the design of the panes. If too many divisions are made, then the view is segmented. No interactions between the outside view and acoustic, thermal comfort, and indoor air quality have been reported.

Shading and Solar Protection

Solar heat and light can be detrimental to IEQ. Excess heat from unwanted solar gains as well as excess light can be controlled by using shading devices and solar protection. Glare is the most common source of discomfort from daylight in classrooms and should be avoided.

The design of these elements will depend on outdoor temperature, sky conditions, orientation, and location of the windows. Shading can be designed as part of the window or an extension of the roof. This strategy will work better on the façade that receives the sun from a higher position (north façade in the southern hemisphere). When the sun is lower on the horizon, horizontal and vertical louvers will be more effective.

3.1.4 Roof

The fifth façade of the building can also affect the IEQ. The selection of materials should be made considering the climate and microclimate where the school will be located. The need of using thermal mass in roofs should be considered when there are large temperature oscillations during the day.

Roof insulation should be carefully considered based on the characteristics of the climate.

The roof can also double as a learning space. Green roofs can provide extra space for outdoor activities and the restorative benefits related to contact with nature.

Roof Windows

Windows placed on the roof can direct light toward deep-lying spaces. As stated before, daylight penetration has limitations so, when spaces are too deep, additional sources of light are needed. It is advisable to provide indirect light, as direct sunlight from the ceiling would produce overheating and glare.

For ventilation, roof windows, if operable, can provide a stack effect. This type of window is commonly used for night-time ventilation since their operation is safer at night than leaving a window open. Special attention should be given to operable roof windows in climates where rain can be expected.

Noise should be considered if roof windows are operable and there are known sources of outdoor noise such as air traffic or busy street traffic.

If windows have low insulation properties, heat stratification can lead to excess heat loss in winter, affecting thermal comfort.

Finishes

Ceilings should consider acoustic panels to achieve the required sound insulation. Sound, similarly to thermal bridges, can be transmitted if the junction between the vertical and horizontal envelope is not carefully designed. Flanking transmission is the structural transmission of sound energy from one room to another and should be avoided by design. Ideally, the ceiling would be white matt as this provides good light reflectance.

3.1.5 Floor

Floor design will impact thermal comfort, because of radiative temperature and visual comfort, depending on color and finish. Acoustic comfort will be affected by the impact and airborne sound insulation of the floor. Both types of noise can be transmitted vertically between adjacent rooms [23].

The finishing material of the floor should be chosen considering that reflections from direct solar radiation can become glare sources. Although dark colors could be used, the contrast between them and the desk should be considered. Therefore, a low reflectance of the floor is recommended. The specularity of the finish should also be lowered if possible [21].

3.1.6 Furniture

The color and finish of the furniture should be designed for avoiding glare. Highly reflective materials are beneficial to distribute light in the room as long as the surface is not glossy, and has a low specularity. This is especially true for desks but should also be considered for other pieces of furniture such as chairs, bookcases, and windowsills. Dark table colors should not be used to avoid high contrast between the work plane (books and notebooks) and the background.

4 Discussion

The first objective of a school should be to provide a safe space for learning, while also giving the best conditions possible to enhance the experience of children. When approaching the design of a school, the designer and stakeholders need to keep in mind that students will spend more time awake at school than in their own houses. At the same time, if they complete their education in the same building, they would have spent 12 years in it. Probably more than the time any adult will spend in the same work environment. Therefore, it is of the utmost relevance to deliver the best design possible.

School design for indoor environmental quality should be faced from a holistic perspective. In the Global South, a passive design perspective will be especially useful as it will reduce operation costs, energy dependence, and maintenance. At the same time, it will make buildings more resilient to natural disasters [30].

The guidelines proposed in this chapter aim at delineating this holistic approach by presenting the different factors that need to be considered to design a classroom.

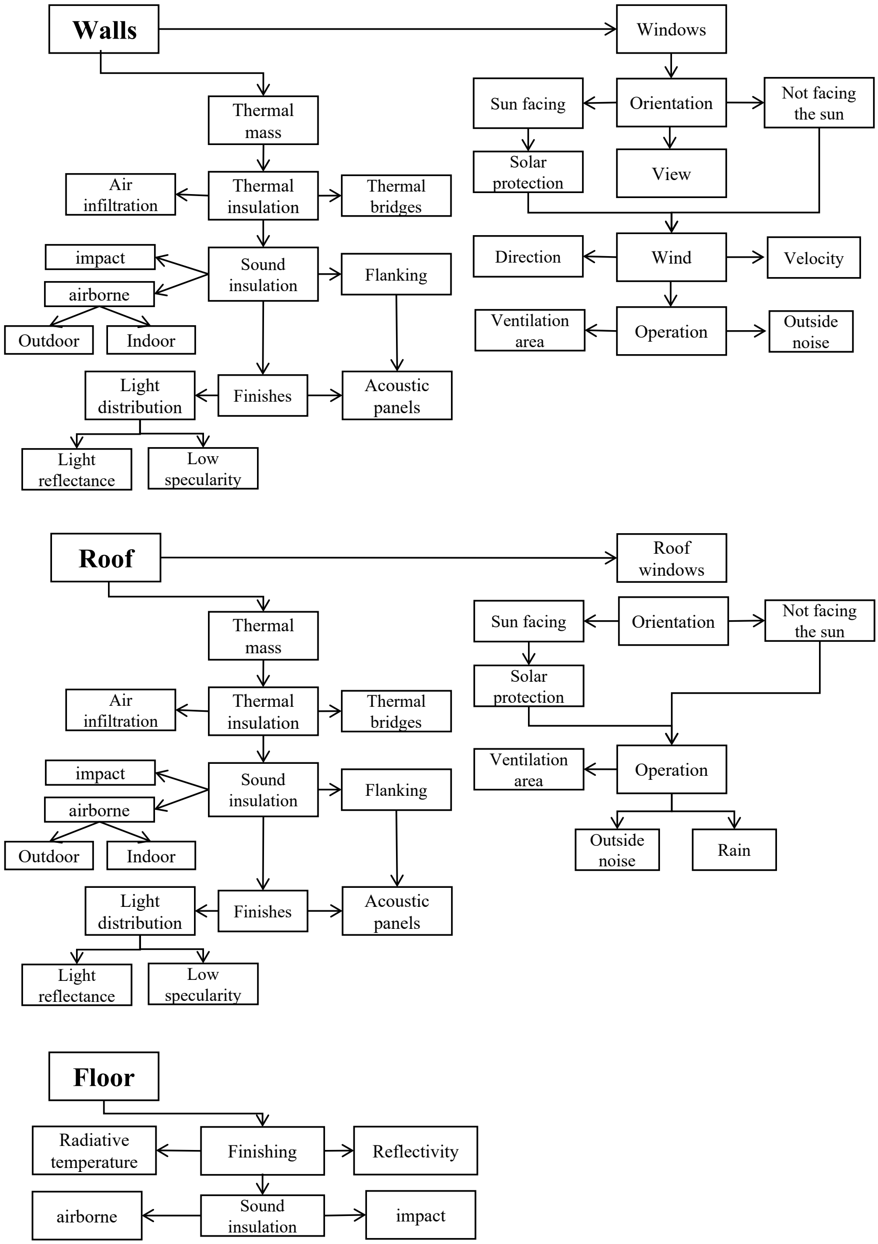

Fig. 1 Design workflow of define passive strategies to achieve IEQ

The design workflow presented in Fig. 1 should work as a guide to achieve safe, healthy, and comfortable classrooms.

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