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Development of a Transdisciplinary Research-Based Framework for the Improvement of Thermal Comfort of Schools Through the Analysis of Shading System

Xabat Oregi [1], Aitor Goti [2,*], Heriberto Pérez-Acebo [3], Irantzu Álvarez [4], Maria-Isabel Eguia [5] and Elisabete Alberdi [5]

1 Department of Architecture, University of the Basque Country UPV/EHU, 20018 San Sebastian, Spain; xabat.oregi@ehu.eus
2 Department of Mechanics, Design and Industrial Management, Faculty of Engineering, University of Deusto, 48007 Bilbao, Spain
3 Mechanical Engineering Department, University of the Basque Country UPV/EHU, Pº Rafael Moreno Pitxitxi, 2, 48013 Bilbao, Spain; heriberto.perez@ehu.eus
4 Department of Graphic Design and Engineering Projects, University of the Basque Country (UPV/EHU), Pº Rafael Moreno Pitxitxi, 3, 48013 Bilbao, Spain; irantzu.alvarez@ehu.eus
5 Department of Applied Mathematics, University of the Basque Country (UPV/EHU), Pº Rafael Moreno Pitxitxi, 2, 48013 Bilbao, Spain; isabel.eguia@ehu.eus (M.-I.E.); elisabete.alberdi@ehu.eus (E.A.)
* Correspondence: aitor.goti@deusto.es

Abstract: This article investigates a methodology for the application of the design of sunlighting and shading systems in educational settings, focusing on their impact on thermal comfort. As educational environments increasingly recognize the importance of physical comfort in enhancing learning outcomes, this study starts with an analysis of current shading practices and their effectiveness. A user-friendly methodology for assessing sunlight and shading in schools is developed, utilizing a transdisciplinary research approach, with various stakeholders, including educators, architects, and environmental scientists. Through case studies conducted in Zornotza, Spain, the research warns about the detrimental effects of inadequate shading on student well-being and proposes design solutions for each of the cases. Our findings underscore the necessity for innovative design strategies that integrate both passive and active shading solutions, ultimately contributing to healthier, more sustainable learning environments. These innovative strategies can be better oriented at the early stages of the analysis of the problem if transdisciplinary research is applied, advocating for a holistic approach to educational facility design that prioritizes the comfort and success of students.

Keywords: shading; shallowing; environmental conditions; school comfort; transdisciplinary research

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1. Introduction

The 2030 Agenda for Sustainable Development is a plan of action for people, planet, and prosperity with the intention of strengthening universal peace and access to justice. This agenda establishes 17 Sustainable Development Goals (SDGs) that seek to address global challenges, such as poverty, inequality, and climate change, promoting sustainable development. To achieve this development, it is essential to harmonize three basic elements: economic growth, social inclusion, and environmental protection [1]. Among the SDGs are several related directly to the educational environment and student well-being [2] as follows:

1. Quality education (SDG 4). An educational environment that meets the principles of quality enhances effective learning and the emotional and social development of students [3].
2. Health and well-being (SDG 3). Integrating health into education not only promotes individual well-being but also contributes to the sustainable development of communities as a whole [4].
3. Sustainable cities and communities (SDG 11). The planning of school buildings, classrooms, and playgrounds should be aligned with sustainable design, contributing to the holistic development of students and moving towards a more sustainable future [5].
4. Climate action (SDG 13). Implementing actions to mitigate climate change can create healthier, safer, and more resilient learning environments, which is critical to student well-being [6].
5. Terrestrial ecosystem living (SDG 15). Fostering students' connection to nature can have a positive impact by helping to reduce stress, improve mood, and enhance creativity [7].

Environmental quality is a topic of growing interest in education and school architecture because it is directly related to student performance, well-being, and learning [8]. Evaluating the environmental conditions of these spaces permits us to establish design strategies for future constructions [9]. Also, in the case of those already built, it enables the identification of adjustments or improvements that allow students to carry out their learning activities in an appropriate manner [10]. This paper deals with thermal comfort in a fundamental area of an educational center: the sunlighting of classrooms.

Thermal comfort refers to the sensation of well-being experienced by individuals in a given environment. Several studies indicate that thermal comfort in classrooms has a direct relationship with students' cognitive performance [11]. When students are exposed to an inadequate thermal environment, they may experience symptoms, such as fatigue, stress, irritability, or distraction, which decrease their ability to retain information and perform tasks efficiently [12]. Conversely, when the environment is comfortable, their attention, memory, and mental processing capacity increase [13]. Some key factors of thermal comfort in classrooms include temperature, humidity control, ventilation, uniform thermal distribution, and lighting, as well as individual and adaptability factors [14]. Consequently, classrooms should be planned according to thermal comfort criteria, which include the choice of materials, building orientation, the installation of efficient heating and cooling systems, and the incorporation of windows that allow adequate ventilation and natural lighting.

Direct sunlight in classrooms affects students in various ways, depending on its intensity and management. While it provides vitamin D, boosts serotonin, and helps regulate circadian rhythms, improving mood, focus, and cognitive performance [15], it also reduces energy consumption and promotes sustainability [16]. However, excessive sunlight can cause glare, hinder reading, and distract students, while raising temperatures and causing discomfort [17]. To optimize sunlight's benefits, solutions like adjustable blinds, tinted windows, or strategic classroom layouts can help manage exposure and minimize distractions. In summary, while direct sunlight can be beneficial in classrooms, managing its intensity is key to creating an optimal learning environment. Ensuring thermal comfort enhances education and supports several SDGs, fostering students' development and promoting a sustainable future.

Along with classrooms, numerous researchers and recognized international educational and public health organizations have highlighted the importance that schools can have on motor, social, sensory, cognitive, and creative development, as well as contributing to improving children's health [18,19].

The space must meet environmental quality conditions that allow all people to develop their qualities without barriers and without losing the aesthetic, functional quality, and creativity of the designers of these environments and buildings [20]. Therefore, the planning of school layouts is essential for learning to be an imaginative, creative, and physically active environment [21,22].

Despite the importance of thermal comfort and shaded areas in schools, research on these aspects is still limited, as is shown in the literature review in Section 2 [22]. This study seeks to address this gap by providing, in Section 3, a user-friendly methodology to assess sunlighting in this type of building. The proposed methodology has been applied in Section 4, in a case study in a village in the Basque Country, which allows for obtaining specific and transferable results to other similar contexts, as commented in Section 4 (Results) and Section 5 (Discussion). Finally, as indicated in the Conclusion in Section 6, by providing tools to assess the sunlighting and shading of educational spaces, the works seek to contribute to the development of healthy and sustainable learning environments that favor the well-being and, consequently, the academic performance of students.

2. Literature Review and Background Studies

Evaluation of both sunlighting and shading in buildings are sound topics in the literature in the last decades. E.g., since the past millennium, software tools, such as the one by Siret [23], have been developed to try to develop intuitive solutions for designers implementing requirements, such as "this area must be sunless the afternon in summer". This means that each of the elements studied in this literature review (sunlighting and shading) has attracted plenty of attention from research.

For example, regarding the management of sunlighting, Piderit Moreno and Labarca [24] developed a climate-based daylight model using Radiance® software v5.4 to evaluate annual lighting performance in classrooms, considering different illuminance intervals and proposing a goal-oriented assessment approach, which is based on their previous methodology developed in Ref. [25]. As well, Leccese et al. [26] present a method to assess lighting quality in educational rooms using the Analytic Hierarchy Process (AHP). Bakmohammadi, P. and Noorzai, E. [27] implement a methodology based on a two-step optimization procedure for the design of primary school classrooms in terms of energy and daylight performance considering occupants' thermal and visual comfort and implementing two series of plug-ins in design software programs. Finally, Costanzo, V., Evola, G. and Marletta, L. [28] and Meng, X., and Zhang, M. and Wang, M. [29] present literature reviews of daylighting strategies in schools, where several methodologies are detailed.

Concerning shading, observational methods, including video recording of students' hat-wearing habits, aerial photography for shade provision analysis, and UV-B exposure measurement using polysulphone film badges, have been successfully implemented to evaluate sun-protection activities [30]. O'Brien et al. [31] developed a methodology for assessing window shade use and its impact on energy use and visual comfort in existing buildings.

All these methodologies provide valuable tools for designers and researchers to assess and improve sunlighting and shading in educational environments. Nevertheless, the joint assessment of both topics in a methodology is relatively rare. In this field, the work by Ishac and Nadim [32] proposes a standardized optimization methodology using genetic algorithms and parametric simulation to optimize daylighting and shading strategies in architectural design. Combining passive design approaches with advanced software, like DaySim, can effectively assess daylighting distribution and daylight autonomy in classrooms [33].

In summary, and as Bakare and Alibaba [14] indicate, research gaps exist in understanding the interplay between thermal, acoustic, and visual comfort factors in classrooms. The existing methodologies to jointly evaluate sunlighting and shading in schools consider the application of relatively difficult techniques.

Thus, as a conclusion of the review, it can be stated that a user-friendly methodology to assess sunlighting and shading in schools could address these research limitations and improve overall environmental quality in schools.

3. Methodology

The methodology applied in this research is transdisciplinary research (TR), in which researchers from various fields may join forces with non-research personnel [34]. TR was selected as the research technique that integrates knowledge across academic disciplines and with non-academic stakeholders to address societal challenges [35]. As is indicated by the same Ref. [35], it is guided by the principle that "scientific rigor meets societal relevance", meaning that it can be less rigorous than other research techniques in favor of a higher societal impact. The general phases for addressing the key challenges of transdisciplinary research are, according to Ref. [36], the following:

- Problem identification and structuring, which require complexity to be reduced;
- Problem analysis, which requires integration;
- "Bringing results to fruition", which is implementing research in practice-oriented solutions for the common good.

It is worth mentioning that these phases pivot from one to the other until a final result is achieved, as defined in Figure 1.

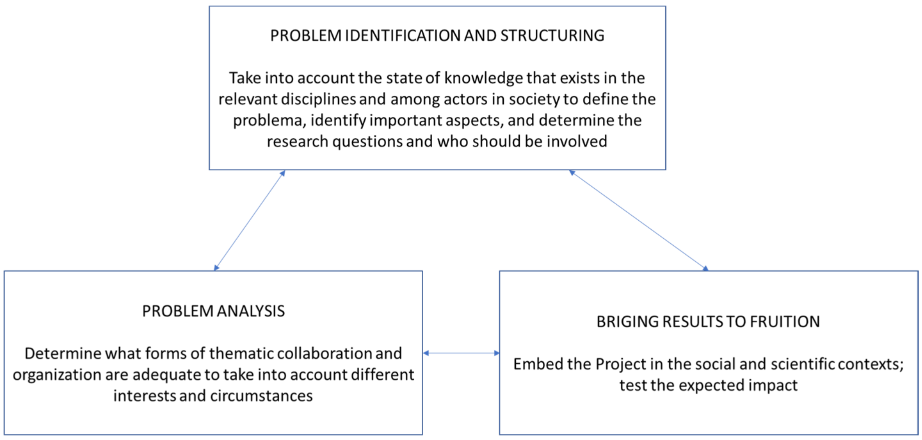

Figure 1. Project methodology and phases of transdisciplinary research [37].

Thus, this transdisciplinary approach was selected because it offers a holistic view and because of its practicality, time efficiency, and ability to transform insights into initiatives with societal benefits [37]. Critics argue that TR may lack rigor and generalizability [38]. However, while the findings may be context specific, they can inform future research and provide practical guidance [39]. And, the purpose of this case was to offer preliminary solutions for the improvement of the thermal comfort of a school through the analysis of the shading system.

The specific TR project discussed in this paper was composed by the multidisciplinary set of authors of the paper who were supported by end users of the studied cases, thus shaping the "Problem analysis phase of the approach". As well, the "Problem identification and structuring" phase of TR was carried out, as detailed in the Introduction (Section 1) and Literature Review and Background Studies (Section 2) of this paper. That work was performed to address and sculpt the "Bringing results to fruition" phase of TR for the complex problem of the improvement of the exposure and shading of a school building in Zornotza, Spain. It is worth noting that the school and building chosen were selected to be part of a project (see the Funding section for further details).

More precisely, in the initial problem identification and structuring phase, the management team in charge of directing the school was the one that started working on this issue since some teachers and students made complaints about comfort. The management team, lacking technical knowledge on how comfort could be evaluated or how the design of the building could influence this type of parameter, first contacted the faculty management that designed and built the building, which then involved the research team authoring this research.

At the problem analysis stage, the work was divided into two groups of activities. On one side, there was the management team, which continued researching the root causes of dissatisfaction related to by requesting more information from the teachers and students who made formal complaints related to thermal comfort and then transferred the information to the research team.

At the bringing the results into fruition step, all the inputs received in the previous stage were analyzed, and the need to commission a technical study was seen in order to assess how the current façade design influences the lighting comfort of students and teachers and how this aspect could be improved. To this end, based on the geometric and construction information of the building, a technical study was carried out, resulting in the proposals presented herein.

Zornotza is very close to the city of Bilbao (Spain). The climate file used to evaluate the climatological characteristics of this case is the Bilbao IWEC (International Weather for Energy Calculation) file. Zornotza is a municipality with an oceanic climate. The average annual temperature is around 14 degrees Celsius. It is a very humid climate; in winter, the temperatures are around 5 degrees Celsius due to the humidity, and in summer, when there is a southerly wind, the thermometers sometimes exceed 35 degrees Celsius. In summer, the average daily temperature is below 20 °C, so no cooling system is necessary. During this period, it is necessary to take advantage of the solar protection systems of the façade openings (recesses, balconies, overhangs. . .), optimize the thermal properties of the roof and sunny enclosures, and perform night-time renovations and/or natural ventilation with cooling in the interior mass of the building when the outside temperature drops below 21 °C. In winter, the average daily temperature is around 10 °C, which requires heating, whose consumption can be significantly reduced by improving the thermal properties of the building envelope and controlling infiltration losses.

When analyzing the behavior of the building envelope with respect to sunlight and shading, there are three points to consider: first, the city and climate where it is located (already summarized), and second, the main orientation of the building. Following the guidelines set by the Spanish Technical Code for Edification regulations (CTE, [40]), the main façade has a southeast orientation with a very high percentage of glazing. Regarding the side facades, one of them has a north orientation and the other a has southwest orientation. In other words, before starting the simulations, it is already known that the windows exposed to the southeast façade may have glare problems, especially in the early morning hours (due to the low solar inclination in the early morning hours). And, finally, regarding the influence of neighboring buildings, it should be noted that due to the orientation, the existing building will not influence the shading of the new surfaces. Furthermore, there is no adjoining building that could influence the solar behavior of the new envelope. However, it is at this point that the importance of the shadows cast by the trees in front of the new southeast façade should be highlighted.

Given the existence of these trees, their shadings were also analyzed. For this purpose, the trees were simulated with totally opaque and spherical objects, as shown in Figure 2 (for the sake of simplicity). The solar simulations were carried out with Ecotect® v1.0 software and its respective applications (Weather Tool and Solar Tool). This very same software was used for the rest of the simulations of the cases.

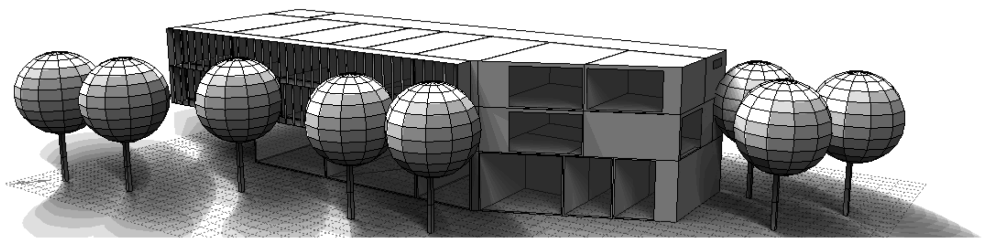

Figure 2. Simulation model of the assets and the trees of the school studied using Ecotect® v1.0 software.

The procedure for the building environment is as follows.: First, both the building and its orientation are established. After that, a specific climate file is defined for this study. In this case, the Bilbao.IWEC climate file [41] is used, which is compatible with Ecotect® v1.0 software. Finally, the "direct shading" is calculated for a given day and time, which allows the following images to be obtained. The azimuth and angle information at each time of the survey is part of the climate file information. And, through these two data, the tool enables the obtention of the necessary data to know how direct solar radiation accesses the modeled spaces.

This study focuses on two zones: Zone 1, lacking shading systems, and Zone 2, with a 1.6 m overhang and vertical shading elements. Zone 1 experiences excessive sunlight, particularly in the morning, leading to discomfort and reduced performance. Zone 2, while better shaded in summer, still suffers from direct sunlight in winter. With the analysis and improvements suggested by the two following cases, it is proven that TR can be a valid tool for the analysis and improvement of sunlighting and shading in schools.

3.1. Analysis of Zone 1

The first study focuses on evaluating and quantifying how excessive sunlight can be reduced to increase the comfort of its users (students and teachers). After numerous complaints from its users, which reflected constant discomfort, we proceeded to evaluate the current state and propose shading strategies that could improve their comfort and increase their performance.

To this end, this study differentiates between two types of zones (Zone 1 and Zone 2; see Figure 3 for details) within the buildings. The first one (labeled 1) is associated with the areas exposed to the southeast with different uses, which do not have any setback or shading system. The second Zone (marked 2) houses the classrooms that have a shading system with a 1.6 m overhang and a mesh or network of vertical elements that will cast shade inside these spaces. On the first floor, there is the music classroom, classrooms for the first and second degrees of secondary students, and a secondary teachers' room, and on the second floor, there are classrooms for the third and fourth degrees of secondary students, a visual and plastic education classroom, and another secondary teachers' room.

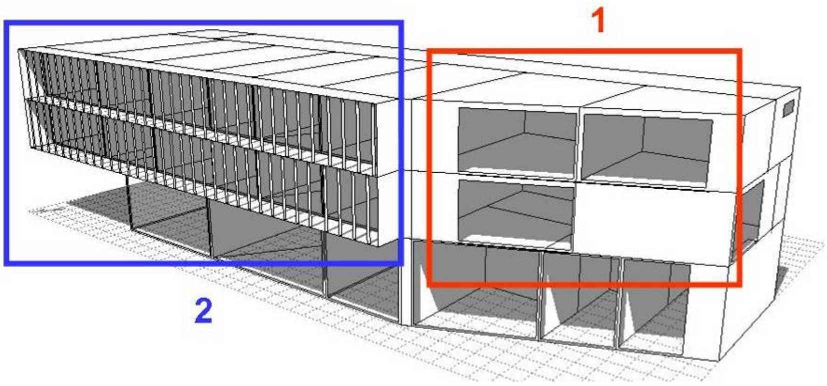

Figure 3. Areas exposed to the southeast (Zone 1 and Zone 2).

In Zone 1, Figures 4 and 5 show how these three glazed openings will receive direct solar radiation throughout the morning, potentially creating problems inside these classrooms.

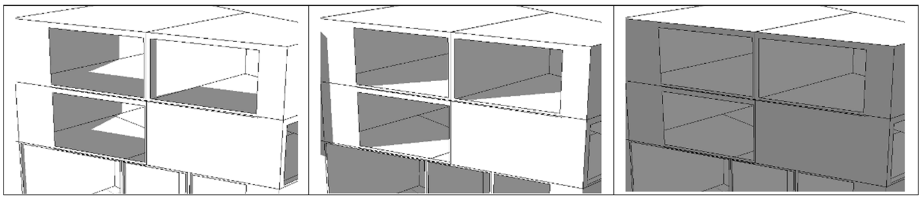

Figure 4. Shadows cast on a part of the façade of Zone 1 during the winter solstice (9:00–12:30–16:00).

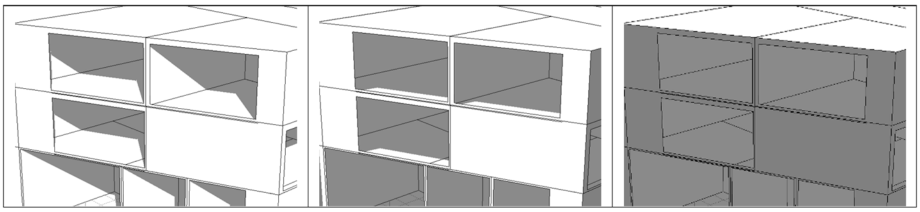

Figure 5. Shadows cast on the façade of Zone 1 during the summer solstice (9:00–12:30–16:00).

Along with the visual study, then, in order to give a real value to this degree of shading, exhaustive calculations (whose results are presented in Tables 1 and 2 and in more detail in the Supplementary Materials) have been carried out, showing different values of the percentage of the effective shading coefficient (ShC) of these gaps. It is worth noting that the ShC comes from the standard shading coefficient (SC), a variable that quantifies the proportion of solar radiation transmitted through a standard 3mm thick single-pane glass window. It is a dimensionless factor ranging from 0 to 1, where 0 indicates complete blockage and 1 represents full transmission. The ShC, as simulated by Ecotect® v1.0 software (software for the design of sustainable construction), provides a more precise measure of shading effectiveness. The ShC is defined as the ratio of solar radiation reaching a surface with shading devices to the radiation that would pass through the standard reference glass.

Table 1. Effective shading coefficient (ShC): monthly mean values for Zone 1.

Month	Mean ShC (%)
January	34.4
February	32.5
March	37.6

Table 1. *Cont.*

Month	Mean ShC (%)
April	42.9
May	46.7
June	46.7
July	43.3
August	42.3
September	39.2
October	34.5
November	34.4
December	32.7
Winter	33.2
Summer	45.6
Year	38.7

Table 2. Effective shading coefficient (CS): extreme days (winter–summer solstice), Zone 1.

Hour	ShC (%) Winter Solstice	ShC (%) Summer Solstice
09:00	0	0
10:00	0	0
11:00	0	0
12:00	0	0
13:00	0	0
14:00	6	100
15:00	49	100
16:00	100	100
17:00	100	100

Looking at the monthly results (Table 1), it seems that the solar behavior of the shaded shafts is quite adequate, as their effective monthly shading coefficient is around 40%. However, when analyzing the daily results (Table 2), it can be seen that in winter and summer, until 14:00 h, the shafts receive direct solar radiation, without any degree of shading.

For this reason, this study proposes different solutions to improve the solar, light, and, therefore, thermal performance of these three openings as follows:

- Decrease the solar factor of the glass to values such as 0.25–0.3. This means that the performance of these glasses improves notably during the early hours of the day; although, in the evening, the demand for artificial lighting and heating in these areas increases (less solar gains).
- Project an external shading system. In this case, given the low solar inclination, it is recommended to use a system of external louvers or blinds, taking advantage of a large amount of diffuse solar radiation but at the same time avoiding problems of glare or overheating. In this case, it is not recommended to design a cantilever system (being a cantilever any rigid object that is fixed at one end and extends out over empty space), as given the dimensions and geometry of the openings and the solar trajectory (low inclination), the degree of shading would still be very low.

- The last solution is to install an interior blind or store system, solving the problem of direct solar incidence and avoiding problems, such as glare or glare problems on computer screens. However, this strategy does not solve the problem of overheating in classrooms, as interior blinds or stores do not prevent solar energy from entering the interior spaces.

3.2. Analysis of Zone 2

Following again TR and with the same purpose of increasing user comfort, it should be noted that this façade contains a second skin or shading system that is complex to introduce into a shadow simulation model (in this case, Ecotect® v1.0 software). Therefore, this network of elements has been simplified by a mesh of vertical elements, trying to resemble as much as possible the effect of the architectural proposal.

Figure 6 shows how in the summer season, the solar behavior of these openings changes substantially with respect to the previous Zone 1, as the 1.6 m overhang and the vertical elements will increase the degree of shading considerably. However, for the winter months (Figure 7), the problem of direct solar incidence in the classrooms remains.

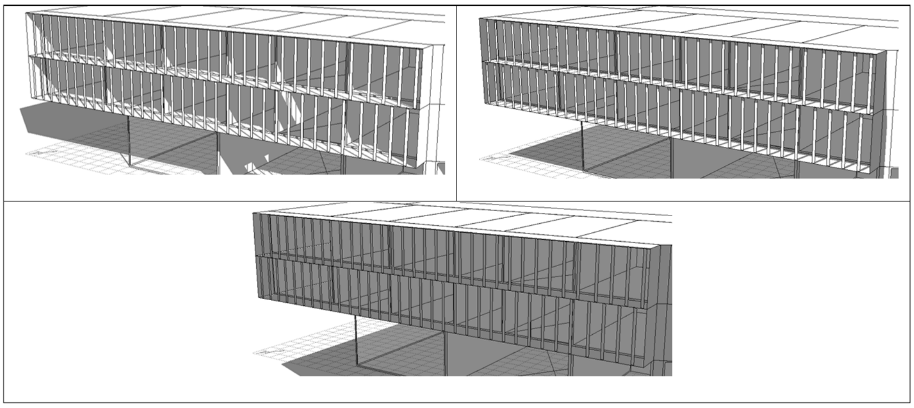

Figure 6. Shadows cast on the façade of Zone 2 during the summer solstice (9:00–12:30–16:00).

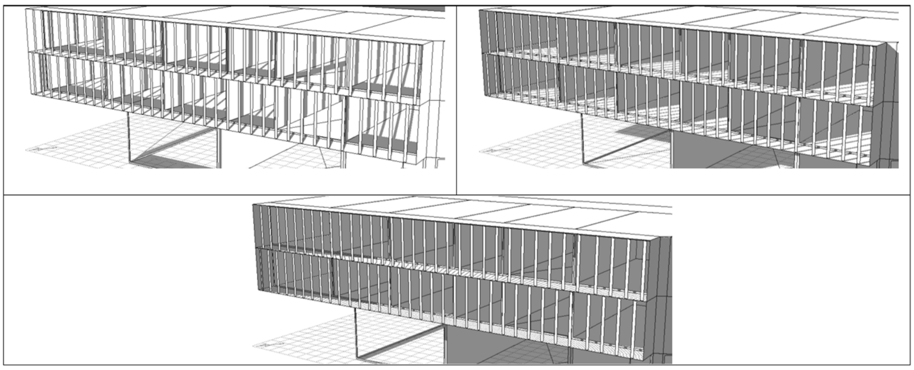

Figure 7. Shadows cast on the façade of Zone 1 during the winter solstice (9:00–12:30–16:00).

Once again, an exhaustive calculation has been made showing different values of the percentage of shading that remains in these openings (see the results in Tables 3 and 4 and the calculations in the Supplementary Materials). With this aim, since the general behavior of all the openings is going to be similar and the most repeated use is a secondary classroom, a central opening has been selected to carry out the calculations of the effective shading coefficient.

Table 3. Effective shading coefficient (ShC): monthly mean values for Zone 2.

Month	Mean ShC (%)
January	48.2
February	60.1
March	68.3
April	75.9
May	86.3
June	87.5
July	85.0
August	76.5
September	68.9
October	57.4
November	46.9
December	42.3
Winter	50.2
Summer	86.3
Year	66.9

Table 4. Effective shading coefficient (CS): extreme days (winter–summer solstice), Zone 2.

Hour	ShC (%) Winter Solstice	ShC (%) Summer Solstice
09:00	18	57
10:00	21	72
11:00	19	90
12:00	31	100
13:00	35	100
14:00	37	100
15:00	40	100
16:00	54	100
17:00	100	100

In this second Zone, looking at the monthly results (Table 3), it is shown that the monthly average of the effective shading coefficient is always above 48%. Together, due to the cantilever system and the double skin of vertical elements, all the openings will have an average annual shading coefficient of 66.9%. In other words, in a climatic Zone, such as Zornotza, an interesting coefficient is obtained (neither too dark nor too light).

With regard to the hourly data, it is shown that the solar behavior of these openings will be very different in each season. The values in Table 4 show that in the winter season, during most of the day, the degree of the ShC is low (below 40%), and these classrooms will receive direct solar radiation and create glare problems. On the contrary, in the summer season, except in the early hours of the day, during the rest of the day, the spaces exposed to this façade will be in shade, only tending to diffuse radiation (recommended for school use).

From all this, it can be seen that the behavior of the cantilever is adequate, generating sufficient shading in the summer season. Otherwise, the problem lies in the months when the solar inclination is low (from mid-October to March), as the solar access will be direct in the classrooms, generating discomfort among users, glare problems, and possible problems when working with computer screens (depending on the position of the furniture). As a result of the evaluation of this area, different strategies are proposed as follows:

- Use glass with a medium solar factor (0.40–0.5), avoiding a high incidence of solar gain. However, it is not proposed to use very dark glass either, as the use of natural light and solar gains are very important energy strategies.
- Due to the orientation of these classrooms (southeast) and the geometry of the glazed openings, it is difficult to optimize the shading system, especially knowing the use and layout of this school. The main problem lies in the winter months, where the solar incidence will be direct (due to the low solar inclination). It is in these months that it will be very difficult to reduce the degree of shading of these openings, as long as a system of louvers or meshing of external horizontal elements is not planned (this solution would totally change the aesthetics of the new skin of the building).
- It should be noted that the shading influence of the exterior vertical elements is considerable and that this is a very appropriate aesthetic strategy and passive solution on the part of the project designer.
- The last solution will be to install an interior blind or store system, especially to avoid the glare effect on students and teachers.

These conclusions for Zone 2 show that unless a new skin is designed with a mesh of horizontal elements (possibly louvers) that cast shadows on the glazed openings, it will be very difficult to avoid the installation of an internal or external louver system due to the orientation of this façade, the geometry of the openings, and the lack of adjacent buildings that cast shadows on it (except for the external trees), particularly to avoid the problem of glare in the classrooms. In the case of installing a system of blinds, this study proposes that they should be installed on the outside of the glass.

4. Results

4.1. Improvements for Zone 1

Once analyzed, and as a consequence of the application of TR, different simulations have been carried out with the aim of quantifying the influence of the strategies proposed in the previous section.

The first proposal focused on decreasing the solar factor of the glass. This change does not imply any variation in the ShC of the opening or its behavior with respect to solar incidence. However, the amount of solar radiation that will access the interiors of these spaces will be significantly reduced, reducing some of the problems of glare and overheating. Otherwise, this effect of darkening or controlling the passage of direct radiation makes these spaces darker, increasing the consumption of artificial lighting and also increasing heating consumption (due to the reduction of solar gains).

The second proposal focused on an external shading system. To this end, this study proposes two types of solutions as follows:

(a) A reflective louver or blind system on the outside of the opening. The strategy is based on fixed or movable louvers with an inclination of 30–40º and a width of 8–10 cm.

This strategy increases the annual shading coefficient by 96%, reaching the average annual ShC value of 75.9%, avoiding a large part of the direct solar incidence, and improving the interior conditions of the spaces assessed in Zone 1 (Figure 8 and Table 5).

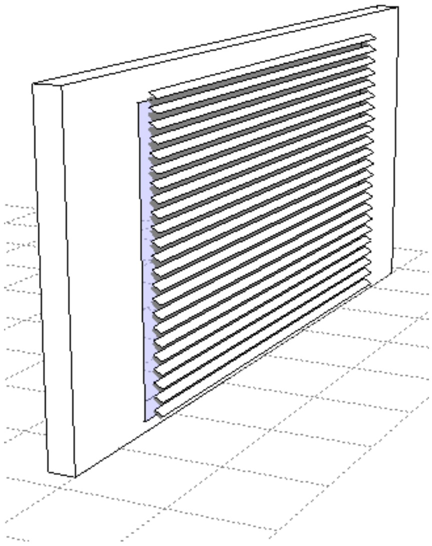

Figure 8. Drawing of strategy 1.

Table 5. Effective monthly shading coefficient for the current and proposed scenario with strategy 1, before and after the implementation.

Month	Present Mean ShC (%)	Mean ShC (%) with Louvers
January	34.4	74.5
February	32.5	74.1
March	37.6	74.4
April	42.9	79.8
May	46.7	77.3
June	46.7	78.1
July	43.3	8v1.0
August	42.3	81.4
September	39.2	73.9
October	34.5	73.3
November	34.4	72.6
December	32.7	70.0
Winter	33.2	72.9
Summer	45.6	78.8
Year	38.7	75.9

(b) A cantilever of 1.6 m. This strategy is based on placing a 1.6 m deep cantilever over the entire length of Zone 1, projecting a linear tracking in the image of the whole building (Figure 9 and Table 6).

Table 6. Effective monthly shading coefficient for the current and proposed scenario with strategy 2, before and after the implementation.

Month	Present Mean ShC (%)	Mean ShC (%) with Cantilever
January	34.4	35.8
February	32.5	39.4
March	37.6	47.0

Table 6. *Cont.*

Month	Present Mean ShC (%)	Mean ShC (%) with Cantilever
April	42.9	51.4
May	46.7	56.8
June	46.7	59.2
July	43.3	54.7
August	42.3	53.2
September	39.2	47.4
October	34.5	37.4
November	34.4	27.4
December	32.7	25.5
Winter	33.2	31.7
Summer	45.6	56.9
Year	38.7	44.1

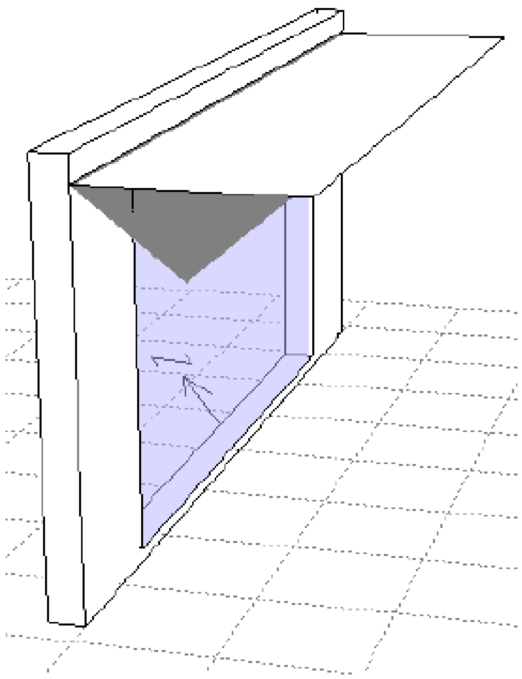

Figure 9. Drawing of strategy 2.

As can be seen in Table 6, the influence of the placement of the cantilever would be very small and would also not solve any glare problems until 11:00–12:00.

Consequently, the best proposal is to install low solar factor glazing and an external shading system.

4.2. Improvements for Zone 2

As we have reflected in the conclusions of the Zone 2 simulations, it will be very difficult to avoid placing any shutter system on the inside or outside of the glazed openings.

Based on the data in Table 5, it is considered that installing a fixed louver system would reduce the possibility of taking advantage of artificial lighting too much, and the visual sensation for the pupils would not be the same either. Therefore, it is proposed that a slat system or movable louvers or blinds be installed on the outside of the glazing, especially if the system is to be used in the winter months and during the first part of the day (between 09:00 and 13:00).

As a final check, the possibility of increasing the dimensions of the overhang has been evaluated, proposing a new depth of 2 m and increasing the overhang by 40 cm. The results of these calculations are shown in Tables 7 and 8 (and calculations are available in the Supplementary Materials).

Table 7. Effective shading coefficient (ShC): monthly mean values for Zone 2, before and after improvements.

Month	Mean ShC (%)	Mean ShC (%) with a 2 m Cantilever
January	48.2	53.7
February	60.1	64.1
March	68.3	73.1
April	75.9	81.9
May	86.3	92.3
June	87.5	92.9
July	85.0	91.1
August	76.5	80.7
September	68.9	72
October	57.4	62.8
November	46.9	49.8
December	42.3	45.5
Winter	50.2	54.4
Summer	86.3	92.1
Year	66.9	71.7

Table 8. Effective shading coefficient (CS): extreme days (winter–summer solstice), comparison of results between a Cantilever of 1.6m and a Cantilever of 2m in Zone 2.

	ShC (%) Winter Solstice		ShC (%) Summer Solstice	
Hour	Cantilever of 1.6 m	Cantilever of 2 m	Cantilever of 1.6 m	Cantilever of 2 m
09:00	18	21	57	73
10:00	21	24	72	89
11:00	19	26	90	100
12:00	31	40	100	100
13:00	35	38	100	100
14:00	37	42	100	100
15:00	40	44	100	100
16:00	54	63	100	100
17:00	100	100	100	100

The increase in the size of the cantilever increases the shading coefficient (SC) by 7%, improving the solar performance of Zone 2. However, as we have seen above, the cantilever was a well-functioning element (especially in the summer season: mid-April, May, June, and September), so the proposal to increase the dimensions of the cantilever is not considered.

As an additional suggestion, and with regard to the ground floor of the new building, it should be noted that a totally translucent space has been designed. In the previous section, it was possible to appreciate the high degree of direct solar incidence that these façades receive. Hence, this report is concerned about the possibility of these ground floor spaces becoming areas with a high temperature in hot months, as long as the strategy of taking advantage of natural ventilation (i.e., to ventilate the ground floor areas) is not considered.

At the same time, it should be noted that the thermal resistance of this type of translucent envelope is much lower than an envelope with insulating material so in winter, the heating demand will increase considerably.

Therefore, this report reflects the concern or doubt about the adequate thermal performance of the fully glazed areas (using the translucent system) on the ground floor.

4.3. Overall Expected Results

Considering both cases together, it can be said that the results obtained in the simulations developed improve significantly the comfort of the students. The agility and positive feedback obtained for embracing end users in this TR approach is also a remarkable detail, as it jointly is (a) a part of a "buy-in" process to obtain the involvement of users in redesign approaches, and (b) it actually enriches the point of view of the TR team.

The aforementioned "buy-in" of end users was obtained by a relatively simple questionnaire filled in by potential users of the assets (teachers and students). This questionnaire consisted of four generic questions related not only to overall thermal comfort (1) but to acoustic comfort (2), air quality (3), and lighting comfort (4). This study was carried out among ten teachers and students. Each person had to score with a value between −100% and +100%, the expected percentual variation of these terms after the suggested actions were implemented (meaning −100% and +100% worst and best case expected improvements). Table 9 shows the number of teachers and students who scored each comfort level during this questionnaire.

Table 9. Results of the questionnaire about the expected improvement by implementing the suggestions resulting from this research.

Expected Improvement % About	Thermal Comfort	Acoustic Comfort	Air Quality	Lighting Comfort
Sample 1	30	5	0	10
Sample 2	20	5	10	40
Sample 3	20	10	10	50
Sample 4	30	20	10	20
Sample 5	50	20	20	20
Sample 6	20	5	20	70
Sample 7	30	30	10	10
Sample 8	15	30	10	25
Sample 9	15	20	15	25
Sample 10	15	20	10	25

As suggested by Ref. [42], with these results, and due to the reduced size of the sample, a bilateral interval of estimation of the average improvement using a t-test was considered an ideal estimator of the forecasted improvement, which was used in Equation (1) as a basis as follows:

$$t = \frac{\overline{x} - \mu}{s/\sqrt{n}} \tag{1}$$

As a result of the application of Equation (1) with a bilateral interval of confidence of 99%, the results of the estimation of the improvement are shown in Table 10 (further details on the calculation are shown in the Supplementary Materials).

Table 10. Estimation of intervals of the perceived performance.

Expected Improvement % About	Thermal Comfort	Acoustic Comfort	Air Quality	Lighting Comfort
Average	24.50	16.50	11.50	29.5
Upper interval	36.33	27.04	17.78	49.84
Lower interval	12.67	5.96	5.22	9.16

5. Discussion

By analyzing the results in Table 10, it is possible to conclude that the expected improvement to be obtained by implementing the suggested initiatives is remarkable. More precisely, and if we approach the analysis of the table from an analysis of the lower interval, we can confirm that the proposed initiatives foresee a positive impact in all the cases by at least a 99.5% rate of confidence. This can be deducted because there are no lower intervals leaving just 0.5% out of the surface of the expected Gaussian population of the improvement.

Evidently, being considered an effective solution does not mean it is actually effective, nor it is actually the optimal one. Thus, the main limitation of this study is that it has not been measured if the suggested proposals are the best possible options. This decision was taken to avoid an excessive wave of suggestions that probably would generate frustration in the non-adopted actions. For the same reason (to avoid excessive participation that could be difficult to handle), the questionnaire-based validation was not extended to the whole population using a reduced sample and applying statistics for obtaining a global estimation.

6. Conclusions

This paper highlights the applicability of a TR approach as a relatively easy method to improve thermal comfort to boost school performance by modifying shading and shadowing systems in buildings. The two actual application cases have obtained successful results. Thus, the TR-based framework for the improvement of the thermal comfort of schools through the analysis of the shading system presented herein is considered valid for the direction of the project and the direction of the school, and it will be considered at a later implementation stage that depends on the funding strategy of the educative entity. Consequently, further research will be oriented to check the validity of the combination of TR techniques for the design of incipient solutions, with other techniques that are profound and consistent so that they can go deeper into detail in the definition of the solutions proposed by TR.

Regarding the cases presented in the paper, further research will be well oriented to fine tune the analysis made. In this type of building for educational use, especially in training classrooms, the internal load is a very important factor that is not defined in this type of analysis. Therefore, it should be noted that this first analysis helped estimate the general thermal needs of the building, as factors, such as internal gains due to occupancy, activity, lighting, computers, etc., are not considered. Thus, further analysis would be oriented to include these elements in the framework.

The research has awakened the interest of FO Interiores for future developments in this line, which is a company that designs spaces. As suggested by practitioners from this company, further research will be oriented to the improvement of the approach in terms of better linking the initial solutions that TR can bring with other methodologies, supporting a more fine-tuned detailed final design. Similarly, the methodology has raised the attention of manufacturing companies, such as the steel company Sidenor, which is keen on testing it in its facilities.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/buildings15010047/s1, File S1: simulation model of zones 1 and 2.

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