"The integral classroom"
Design strategies for improved overall environmental performance

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ABSTRACT: The architectural design of a school classroom has an effect on students' wellbeing, as thermal, visual and acoustic comfort, as well as indoor air quality, characterizes learning environment. This paper explores design strategies for school classrooms that aim at improving environmental performance in an integrated manner, looking for "integral classrooms" prototypes. The context of the study was based in Chile, organizing the country into three macro-climatic zones (north, central and south) in order to propose appropriate design strategies for each zone. Thermal design strategies for north and central zones focused mostly on avoiding overheating, while strategies for the south zone focused on making use of solar gains. Daylighting strategies were focused on reducing the risk of glare and improving daylight uniformity. Thermal simulation looked at heating and cooling energy demand; daylighting simulation looked at six daylighting parameters under different sky conditions; and acoustic simulation looked at insulation and reverberation time. The results showed that most integral classrooms proposals performed adequately under specific climatic conditions, although those strategies that improved daylighting performance (such as achieving better uniformity with solar control devices) involved worse thermal performance, as they reduced solar gains; while the opposite effect was also evident.
Keywords: school classrooms; design strategies; visual comfort, thermal performance; acoustic performance.

INTRODUCTION
School buildings with good environmental performance can considerably improve the attention capacity, concentration, learning, hearing and behaviour of the students [1]. It is argued that spaces designed with an understanding of how children respond to the properties of the space can contribute to creating an environment that favours the student's learning performance [2]. In practice, if the students feel uncomfortable or distracted by noise, by poor lighting conditions, due to the lack of heating, cooling and/or ventilation, their capacity to learn will be affected. It is important that planners and the designers of schools see, in their task, an opportunity to create better settings for learning, as a tool which favours academic performance.

This paper starts from research carried out to generate a design guideline for school classrooms led by a foundation which promotes energy efficiency in Chile [3]. It was thought out as a task prior to school building design which promotes strategies for different climatic areas of Chile, promoting an integrated vision to face the architectural project.

Given the length of Chile, this study divided the country into 3 macro-zones; north, central and south, in order to generate strategies adapted to the local climatic conditions. Diverse passive design strategies, which together aimed at energy efficiency and environmental comfort, were proposed and analysed. These proposals are called "integral classroom", their objective is to integrate the strategies of thermal, lighting, acoustic and ventilation design, analysing their effects based on simulations. The designs of each "integral classroom" were made through multidisciplinary work with specialists. From a preliminary study [4], the environmental variables to be resolved for each one of the 10 cities included in the study were defined. For the north macro-zone, the cities of Calama (desert), Copiapo (North zone transversal valleys), Iquique (North zone coastal). For the central macro-zone, Valparaiso (coastal), Santiago (central inland) were studied, and finally for the South Macro-zone Colchane (Andean zone), Concepción (coastal), Temuco (inland) and Punta Arenas (extreme south).

INTEGRAL CLASSROOM PASSIVE DESIGN
For this study 4 types of "integral classroom" were defined based on the most commonly used configurations in Chilean public educational facilities. A base classroom of 6x9m, that is 3m high, was defined. The corridors were defined as per standard [5], open corridors for the north and central macro-zone and closed corridors in the south macro-zone. The effect of a geothermal heat exchanger tube or "Canadian well" was considered on the heating and cooling demands for the north and central macro-zone classrooms. This system

allows preheating or cooling the incoming air, providing thermal comfort and warm air in the classroom. A 40cm diameter, 30m long tube, located 3m underground, was used. For the case of the south macro-zone, the effect of a heat recovery system on the heating requirements was simulated. This would allow taking advantage of the heat of the air that is taken from the classroom to preheat the clean air that enters from outside, also satisfying the ventilation requirements. The thermal insulation varied for all classrooms depending on the climatic area. Considering all the previously noted restraints, the designs described below, were deduced. For the acoustic design in the design strategies, acoustic absorber panels were included in the rear wall of the classroom and double-glazing for all the integral classrooms.

"Integral classroom 1" with double centreline on two north-south facing floors (see Figure 1), to protect and distribute the light on the North-facing façade, internal and external lightshelves are included on the classrooms of the North and Central macro-zones, and only internal for the South macro-zone. The classrooms receive indirect lighting from the corridor with double centreline on those located on the ground floor, which generates openings on the upper corridor for better light distribution. Ventilated roofs to avoid overheating are considered, in addition, the length of the north overhang of the corridor's cover is increased to achieve glare protection in the classrooms to the South of the first floor. When the design is adapted to South macro-zone requirements, a protected corridor is considered, including ventilation screens over the windows.

"Integral classroom 2" is a simple centreline block with double orientation, designed to be used with East-facing classrooms with West-facing corridor and West-facing classrooms with East-facing corridor (see Figure 2). The classrooms have a vertical sunlight protection system, to protect them from the incidence of direct sunlight in the morning or afternoon, depending on the orientation, combined with lightshelves to improve daylight uniformity inside. To reinforce the lighting strategies, indirect lighting is considered on the ground floor as well as diffuse lighting, provided by a high level window, which includes lightshelves, on the first floor. It is considered to ventilate through crossed ventilation on the ground floor and convective ventilation on the first floor. As the design is adapted to South macro-zone demands, the corridor is closed with windows that can be opened on the façade.

"Integral classroom 3" is a simple centreline block, with East-facing classrooms and West-facing corridor, or West-facing classrooms and East-facing corridor (see Figure 3). A well, formed by translucent panels with screens incorporated, is placed in the corridors to ventilate and illuminate. The translucent area in the upper part of the well helps to heat the air and generate greater temperature differential, increasing the Stack effect. The support of diffused daylight is done through high windows integrated in the classroom; at the same time, these windows can be opened to allow stack effect ventilation. The classroom's external façade considers vertical screens on the windows, with lightshelves above these. For the South macro-zone, these strategies were considered applying them on classrooms with double centrelines.

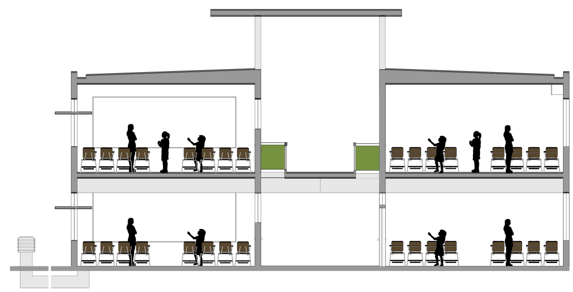

Figure 1: Passive strategies applied "integral classroom 1"

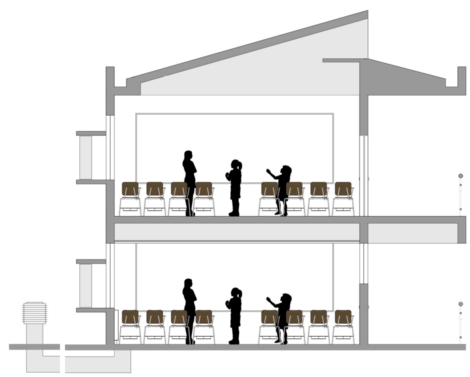

Figure 2: Passive strategies applied "integral classroom 2"

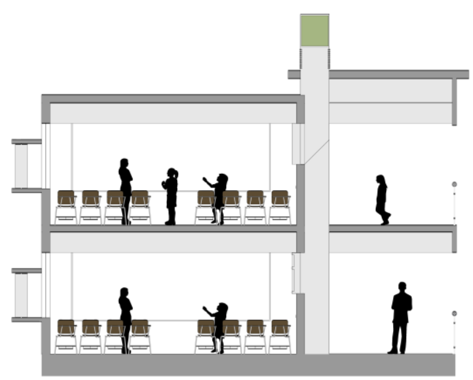

Figure 3: Passive strategies applied "integral classroom 3"

"Integral classroom 4" is a simple centreline block, South-facing classroom with North-facing corridor (see Figure 4). It captures direct sunlight through a skylight located in the centre of the first floor classroom, considering translucent baffles to avoid glare and operable openings to generate stack effect ventilation by opening windows. The daylight source for the ground floor is through indirect sunlight from the corridor, which considers cross ventilation. The windows located on the South-facing façade provide diffuse daylighting and views. When the prototype is located in the South macro-zone, the North-facing corridor incorporates Trombe walls to contribute to the classrooms' thermal balance.

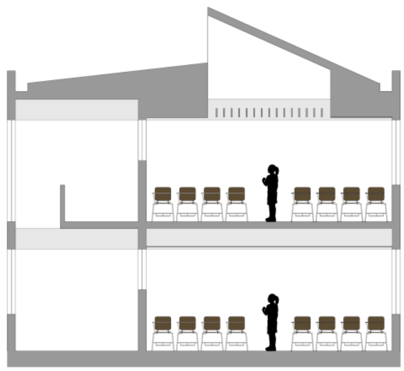

Figure 4: Passive strategies applied "integral classroom 4"

ANALYSIS METHODOLOGY AND SIMULATION

With the objective of having an integral study for the design guide developed, the thermal, lighting and acoustic study of "integral classroom 1" and "integral classroom 2" were carried out in the 10 cities represented. Differentiated methodologies were used, whose final objective was to determine the overall performance. In this paper the methods used for the thermal, lighting and acoustic analysis, are described.

The purpose of the thermal study was determining energy demands for heating and cooling the school classroom, as well as the total energy demand (kWh/m^2 year). The simulation parameters are presented in the figure 7, 8 & 9 corresponding to three representative cities of each macro-zone, Iquique, Santiago and Punta Arenas. The input values of the thermal variables are deduced from a preliminary study. Canadian well and heat recovery system were considered for simulation. The Canadian well was simulated with EnergyPlus through the ZoneEarthTube module, where the ground conditions were determined with the CalcSoilSurfTemp program. The heat recovery system was simulated with DesignBuilder, through the HVAC compact option, with a heat recovery efficiency of 70%. For each classroom studied, the comparative results were graphed between the situation with and without the aforementioned systems.

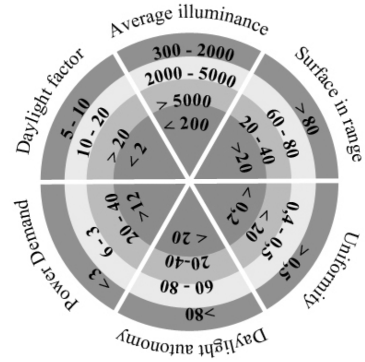

Figure 5: Performance scale of daylight factor, Average illuminance, Surface "In Range", Uniformity, Daylighting autonomy, Energy demand.

The lighting study fixed the objective of getting to know the distribution, amount and quality of daylight. It determined the illuminance level on the horizontal work plane through software Radiance. Simulations were run for the equinox, winter solstice and summer solstice, evaluating at 9:00 am, 12:00 pm and 15:00pm under two sky conditions, for the North macro-zone under intermediate and clear sky, and for the Central and South macro-zones under overcast and clear skies. Six performance indicators were used: daylight factor (overcast skies), Average illuminance, Surface in range, Uniformity, Daylighting Autonomy and energy demand for artificial lighting purposes. Expressed in a "dashboard" where each segment is associated to an indicator and to their respective metric (see **Figure 5**), where the largest slice indicates that it is reaching the design objective, whereas getting smaller means that the proposed design strategy should be restated in order to meet the design objective, allowing us to quickly understand the annual results of the different strategies.

The acoustic study was made for each classroom's geometry, independent of the place. The methodology consisted in the analysis of two scales: the classroom was evaluated as a whole, as well as the constructive elements it is made of. To analyze the behavior of the acoustic insulation to aerial noise and from the impact of an integral building, considering the transmission roads through the sides, the SONarchitect ISO software was used, whose calculation method corresponds to that detailed in the UNE EN 12.354 norm [6], parts 1 and 2. The acoustic insulation entry data of the construction elements was calculated with the INSUL software, whose algorithms correspond to models based on the works done by B.H. Sharp, Cremer and others [7, 8].The acoustic behaviour inside the classroom is obtained by the EASE simulation software, whose calculation method is based on the sound absorption data from the internal floor covering, and the geometric parameters of the room, such as the surface and volume. The sound absorption entry data of the materials is obtained using the ZORBA software.

INTEGRAL CLASSROOM EVALUATION

The results of the three cities of Chile that characterize the different macro-zones: Iquique, Santiago and Punta Arenas, are presented. The integral classrooms presented correspond to the “integral classroom 1” prototype with double centreline for the North facing floors located in the first floor (Figure 1) and "integral classroom 2" prototype with a simple centreline block, East-facing with a West-facing corridor located on the first floor (as seen in Figure 2).

Iquique is a coastal city at 20º32' latitude South and 70º11' longitude West, with desert coastal climate. The average temperature is 21ºC in summer months and 15º in winter months, with an average relative humidity (RH) of 74. The results of the studies are shown in Figure 7.

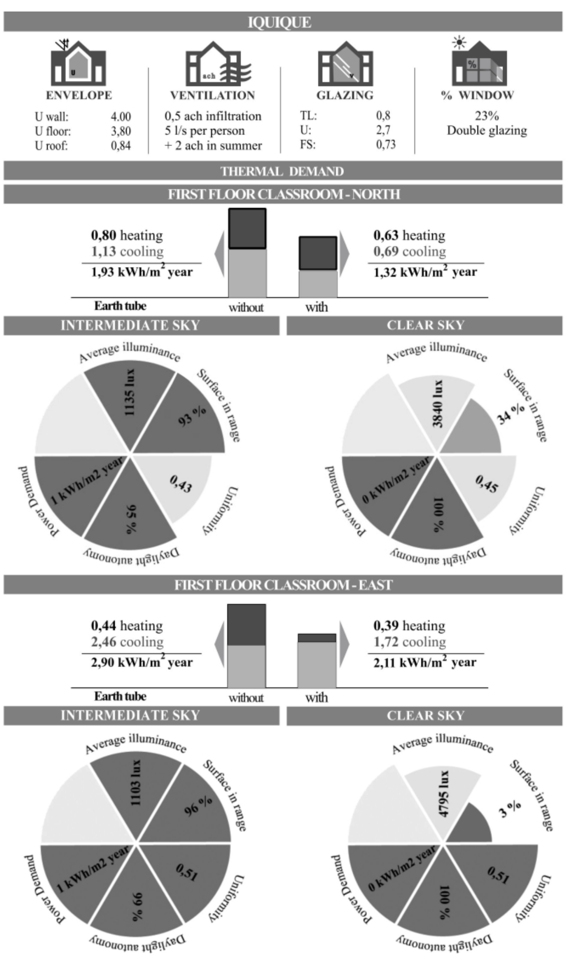

Figure 7: Input and thermal and lighting results "integral classroom 1" and "integral classroom 2" in the city of Iquique

For the “integral classroom 1” and “integral classroom 2”, heating and cooling energy requirements are not very significant, so the incorporation of a Canadian well is not justified. As for the daylighting performance, "integral classroom 1", has a good performance with intermediate sky, only the uniformity does not reach its target value. With clear skies, "integral classroom 1” presents an area next to the window with high illuminance that affects the uniformity and increases the average illuminance over 2000 lux, which affects the surface found “in range”. In the “integral classroom 2”, the lighting performance for intermediate skies is excellent, the Average Illuminance of 1103 lux, 96% of the Surface on Ranges between 300-2000 lux, the average Uniformity reaches 0.5 and 99% of Daylighting Autonomy. With clear skies, the solar protection strategy is not enough; the Average Illuminance increases to 4795 lux, having only 3% of the Surface in Range. The solar protection must be restudied or recur to mobile solar protection. Other indicators such as Uniformity, Daylighting Autonomy and Power Demand reach their target values.

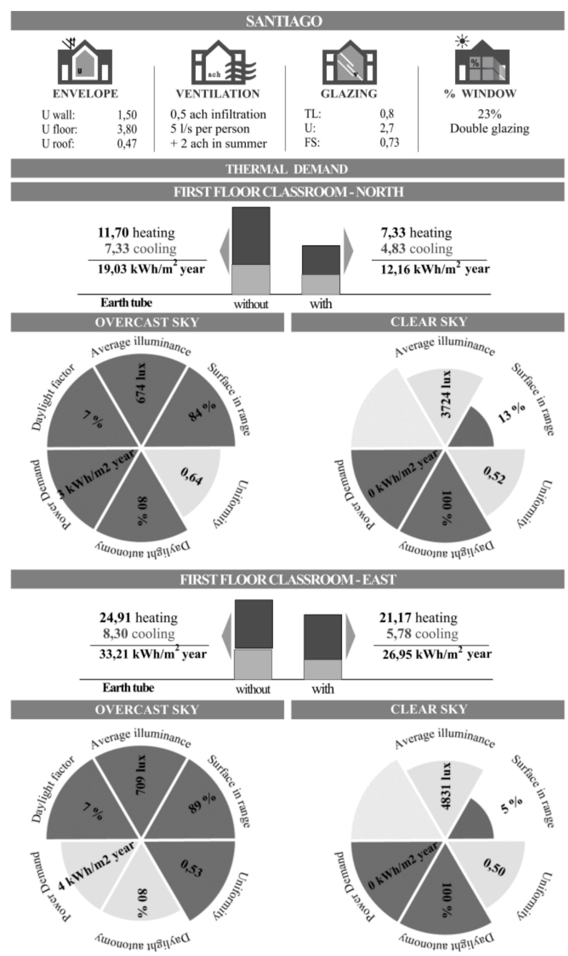

Figure 6: Input and thermal and lighting results "integral classroom 1" and "integral classroom 2" in the city of Santiago

Santiago is at the foot of the Andes Mountain Range, at 33º26' latitude South and 70º41' longitude West. The average temperature in summer is 20.1ºC and 9.2ºC in winter, with large daily thermal oscillations. From the thermal analysis it was determined that the incorporation of a Canadian tube manages to reduce the heating and cooling demands by approximately 40% in "integral classroom 1" and by 20% for "integral classroom 2". In this climate, this technology is even more justifiable as the demands are more important than the climates in the north of the country (see Figure 7).

Punta Arenas is at 53º8' latitude South and 70º53' longitude. In winter, it has average temperatures between 0ºC-5ºC and in summer between 6.6ºC and 15ºC. The lighting performance of "integral classroom 1" with overcast skies was good, reaching a daylight factor of 6%, Average Illuminance of 674 lux and 86% of the surface in range.

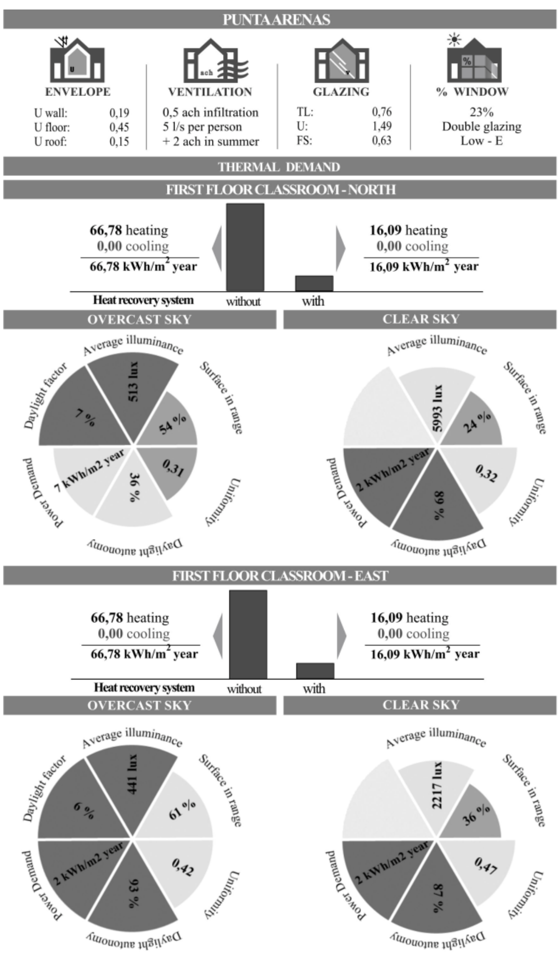

Figure 7: Input and thermal and lighting results "integral classroom 1" and "integral classroom 2" in the city of Punta Arenas

With clear skies it achieves a very high average illuminance, affecting the surface in range, it is recommended to complement with greater solar control. For the "integral classroom 2" with cloudy skies, it reaches a Daylight Factor of 7%, reaching the objective values in Average Illuminance, Surface In Range and Uniformity. With a small reduction in the Daylight Autonomy reaching 80% and the energy demand for artificial lighting is 4 KWh/m^2 year. With clear skies, the average illuminance rises to 4831 lux, which produces a reduction in the surface in range to 5%, a large percentage of the surface with illuminance over 2000 lux.

The incorporation of a heat recovery system implies a reduction of approximately 70% in the heating demand in "integral classroom 1", which is very significant; above all if it is considered that it also covers the ventilation needs. In the case of "integral classroom 2", it reduces by 40%. Even with the incorporation of this system, this will require additional heating. For daylighting performance, in the case of "integral classroom 1" in the two skies analysed it was seen that the strategies do not have a good uniformity, with overcast skies we have greater surface in range, but a low autonomy. On the contrary, with clear skies an excellent autonomy, but the Average Illuminance is over 5000 lux. In the case of "integral classroom 2" with cloudy skies reaches the objective values in most of the indicators; however, it obtains 61% of Surface in Range as in winter months it obtains very low illuminance. With clear skies, the average illuminance increases to 2217, reducing the surface found "in range" to 36%, very low.

From the results obtained in the acoustic analysis applied to the classrooms geometry, referring to the intelligibility of the word, it is concluded that "integral classroom 1", has Word Intelligibility valued as "Good" on 80% of the surface occupied by the students. The remaining 20% is valued as "Excellent". For the case of "integral classroom 2", it has Word Intelligibility valued as "Acceptable" on 27% of the surface used by the students. The remaining 70% is valued as "Good", while only 3% is valued as "Excellent". The construction elements comply with the requirements established for acoustic insulation from aerial noise of the façade and between classrooms (horizontal and vertical) and for noise emitted from an upper floor.

CONCLUSION

Starting from the case study applied on such an extensive territory, the following is concluded in relation to each macro-zone. Of the different cities in the North Macro-zone, it can be concluded that the heating and cooling energy demands are quite low, for which the incorporation of a Canadian well does not generate a significant effect. In general, the North-facing "integral classroom 1", with internal and external lightshelves, has the best performance. The strategies applied using natural ventilation and the thermal envelope values proposed manage to reduce the energy demands; likewise, it has a good lighting performance reaching the target values. All the strategies proposed require some type of solar control under the shelf, especially for clear skies in winter where the incidental angle causes a greater penetration of sunlight. "Integral classroom 2" has a good control of incident sunlight inside the classroom, thanks to the sunlight control strategies of the façade with vertical elements, as well as a high window with translucent glass, which allows for an excellent coverage and a controlled incidental sunlight.

The results obtained from the classrooms studied in the Central Macro-zone conclude that the incorporation of a Canadian well allows reducing heating and cooling demand by 40%, which is significant. In general, the classrooms with inclined roof with a high window have high-energy demands, attributed to the glass surface and a higher volume of air to be heated. The lighting strategies proposed here reach a good lighting performance reflected in the percentage of the classroom's surface with illuminances in the range necessary to carry out the different visual tasks. In the case of integral classroom 2, with vertical protection, the results indicate that for overcast skies, there will be moments in which the illumination must be complemented with artificial lighting, which is why we conclude that it is necessary to re-study the distances of the vertical sunlight protections applied.

For the case of the South Macro-zone classrooms, characterized by their high heating demands, it is concluded that a high standard thermal covering needs to be considered, DVH and Low E windows, and low levels of air infiltration. With these strategies in the southernmost cities, the demands without heat recovery are increased due to the heat losses associated to ventilation. As a result of this, the incorporation of a ventilation system with heat recovery is very efficient, as it reduces the demand by between 70 and 90%. The proposed illumination strategies present a good lighting performance with clear skies; however, with overcast skies in most of the cases studied, the objective for daylighting autonomy is not reached and it must be complemented with artificial lighting.

In terms of school classroom designs it is concluded that it is possible to reach a good energy performance by integrating the different environmental, thermal, lighting, acoustic and air quality parameters, as long as they are included in the architectonic response, being able to reduce the energy demand in the schools through passive design without needing to integrate active systems. It is important to highlight that the architect has a prevailing role, as the design decisions affect the classroom's performance.

From the interdisciplinary work in the design stage, it can be concluded that the early involvement of the specialists allowed us to reduce the iterations and arrive more quickly at an optimal solution for the integral classroom, thus allowing quickly reaching an in-depth study of thermal, lighting and acoustic parameters. From the "integral classroom", it can be concluded that, although there are a great variety of design strategies proposed these are not definitive, and they can serve as the base and guide for future designs.

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