# Application of an Indoor Greenhouse in the Energy and Thermal Comfort Performance in a Kindergarten School Building in the South of Portugal in Winter Conditions

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*Abstract:* - In this work a numerical model, which simulates the buildings thermal response and evaluates the indoor environment comfort, in transient conditions, is used in the application of an indoor greenhouse in the energy and thermal comfort performance in a kindergarten school building, in the South of Portugal, in Winter conditions. In the numerical simulation of the kindergarten school building, the 25 compartments, the 498 building main bodies and the 42 windows glasses, as well as two schools and three residential surrounding main buildings, are considered. This numerical model is applied in the evaluation of the kindergarten thermal behavior, using the indoor temperature field, and the occupants thermal comfort levels, using the PMV and PPD indexes.

After to be compared the numerical and experimental indoor air temperatures field and identified the indoor thermal uncomfortable spaces, the numerical model is used in the evaluation of the indoor greenhouse performance, in order to increase the indoor air temperature and thermal comfort levels, using solar renewable energy, without increase of the kindergarten energy consumption. It is analyzed in detail the greenhouse ventilation operating time and the warm airflow transport way, using an internal ducts system or a corridor space, from the greenhouse to the indoor coldest spaces.

*Key-Words:* - Kindergarten school building, Numerical simulation, Experimental tests, Building thermal behavior, Energy, Indoor greenhouse, Thermal comfort.

## 1 Introduction

In the Algarve region, in the South of Portugal, it is very important to develop kindergarten school buildings, adapted to this region, that can promote the increase of the occupants comfort conditions, namely the thermal and air quality, as well as to promote the reduction of energy consumption levels for the buildings.

In Winter conditions renewable resources, like direct solar radiation, in order to increase the indoor air temperature level, are used. The energy management in this kind of situation, in order to obtain a better thermal comfort field inside a building environment, is frequently analyzed using building thermal behavior numerical models.

In [1], as example, a school building thermal response, located in the South of Portugal, in a Winter typical day using a numerical model that simulates the thermal behavior of a building with complex topology and evaluates the indoor air quality, in transient condition, was made. The idea of the study is to reduce the buildings energy consumption and increase the occupants' thermal comfort levels, using the high solar radiation levels disposable in this region. In the first phase the uncomfortable rooms were identified, in the second phase the electric air heating systems with PMV index control were numerically installed and, in the third phase, three air collectors located above the roof area to heat the air to be injected in the uncomfortable rooms were numerically analyzed. In the first phase were verified that, in general, the rooms with windows turned North, the compartments with windows subjected to shading devices and the indoor spaces without windows with low occupation level, presented the highest uncomfortable thermal conditions. The installation of electric air heating systems in uncomfortable spaces promoted good thermal comfort levels. It was verified that using the PMV index control is possible to guarantee high comfort levels with lower energy consumption levels in the heating process. The highest consumption level was verified in the first hours of the day, mainly in compartments with main occupation time verified during break times. In the third phase was verified that the solar air collectors promoted, in the afternoon, acceptable thermal and air quality levels in the considered spaces. In this phase, in order to promote simultaneously thermal and air quality good levels, was verified that the uncomfortable occupied spaces are ventilated and heated using warm air from the collector, the comfortable or lightly comfortable spaces are ventilated and heated using lightly warm air from the corridor and the small comfortable occupied spaces are ventilated using clean air coming directly from the outdoor environment.

In order to evaluate the thermal comfort level in moderate environments equipped with air-conditioning systems, either in cold or in warm climates, during Winter or Summer, the PMV (Predicted Mean Vote) and the PPD (Predicted Percentage of Dissatisfied) indexes are used (see [2] and [3]). For acceptable thermal comfort conditions, the [3] defines three comfort categories (A, B and C), establishing limits for PMV and PPD indexes. This classification allows the selection a priori of one thermal environment accord to the required demands.

The life quality, the energy management and the human health has been an important issue analyzed in the last years. The increases of quality of life in the modern city, for example in [4], the energy consumption and exhaust emissions reduction, for example in [5] and [6], and the atmosphere air quality, for example in [7], are some practical examples of this issue. In the last issue, related to the human health, special interest are being shown in the development of efficient buildings, which proportionate highest comfort levels, with low energy consumption level. The study of buildings materials in order to evaluate the thermal system in building constructions and the energy building consumption, for example in [8], the energy save measurement in commercial buildings in order to improve the building energy performance and to reduce the fuels consumption, for example in [9], the use of solar air collector integrated in a shutter or others systems, in order to increase the indoor air quality, for example in [10], and the use of radiant ceiling panels installed in indoors spaces or other systems, in order to increase the comfort level that the occupants are subjected, for example in [11], are some practical examples of this issue.

In this work a numerical model, which simulates the kindergarten thermal response and evaluates the indoor environment comfort, in transient conditions, is used in the application of an indoor greenhouse in the energy and thermal comfort performance in a kindergarten school building, in the south of Portugal, in Winter conditions. The work is divided in five parts: in the first one the numerical values are compared to the experimental measured data, in the second one the indoor temperature field is used to identify potential spaces used as indoor greenhouse with enough capacity to heating the air, in the third one the indoor thermal comfort level, using the PMV and PPD indexes, that occupants are subjected, in the fourth one the indoor temperature field using an indoor greenhouse with capacity to use the solar radiation in the indoor air heating and in the fifth one the indoor thermal comfort level, using an indoor greenhouse, that occupants are subjected, are evaluated. In the last two parts the greenhouse ventilation operating time and the warm airflow transport way, use an internal ducts system or a corridor space, from the greenhouse to the indoor coldest spaces, are analyzed.

## 2 Numerical Model

The multi-nodal buildings thermal behavior model, which operates in transient conditions, is based in energy and mass balance integral equations (see [12], [13] and [14]). The energy balance integral equations are developed for:

- the air (inside the several compartments and ducts system);
- the different windows glasses;
- the interior bodies (located inside the several spaces);
- the different layers of buildings main bodies and ducts system.

The mass balance integral equations are developed for:

- the water vapor (inside the several spaces, ducts system and in the interior surfaces);
- the air contaminants (inside the several spaces and ducts system).

In the resolution of this equations system the Runge-Kutta-Fehlberg method with error control is used. The model considers the conductive, convective, radiative and mass transfer phenomena:

- the conduction is verified in the building main bodies (doors, ceiling, ground, walls, etc.) and ducts system (fluid transport) layers;
- in convection the natural, forced and mixed phenomena are considered;
- in the radiation, verified inside and outside the building, the short-wave (the real distribution of

direct solar radiation in external and internal surfaces) and long-wave (heat exchanges between the buildings external surfaces and the surrounding surfaces as well as among the internal surfaces of each space) phenomena are considered. In radiative calculus the shading effect caused by the surrounding surfaces and by the internal surfaces is considered.

## 3 Building Simplified Geometry

In the analyzed kindergarten school building (see Figure 1), divided in 24 compartments (see identification in figure 2), 498 building main bodies and 42 windows glasses are considered. This building, located in Olhão, has three classrooms, for 3, 4 and 5 years old children, and other spaces for offices, administrative, WC, teachers and non-teachers staff and meeting room.

In Figures 1 the grid generation used in the numerical simulation of the kindergarten school building is presented. This numerical grid, used in the internal and external direct solar radiation determination, was spaced 30 cm in both directions.

## 4 Results

In this study the software that simulates the buildings thermal response, with complex topology, in transient conditions, and evaluates the indoor thermal comfort and indoor air quality levels, is used. This software was validated in Winter (see [13]) and Summer (see [14]) conditions, in school buildings with complex topology. Nevertheless, in this work, before the evaluation of the building thermal response and occupants thermal comfort conditions, the software is also validated considering the surrounding buildings.

In this numerical model validation the doors and windows were closed, the internal curtains were open, the air-conditioning systems were off, the occupation is not considered and the indoor radiative heat exchanges were also not considered. The air mean renovation values inside each compartment by infiltration were experimentally obtained, in several compartments, using the tracer gas concentration method. In the school buildings numerical simulation, in order to evaluate the real building thermal inertia, the previous 5 days were also simulated. The experimental test, used in the validation phase, was made in a day without external wind.

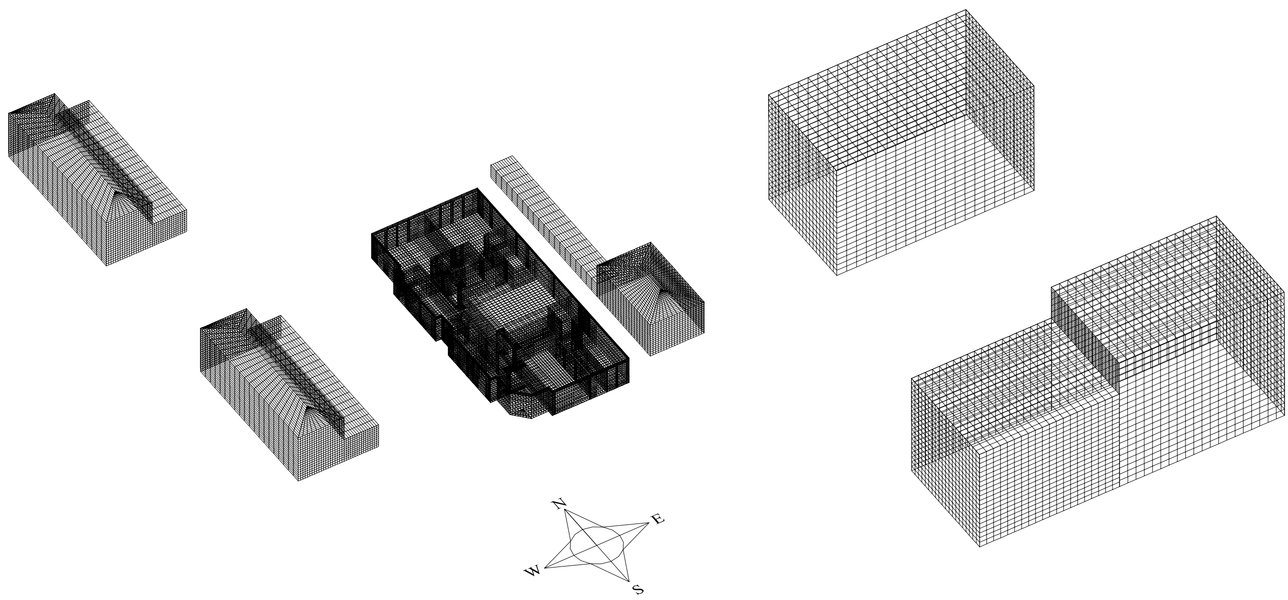


Figure 1. Grid generation in the kindergarten school building and surrounding buildings. This geometry is based in the “Jardim-de-Infância n.º 4 de Olhão”.

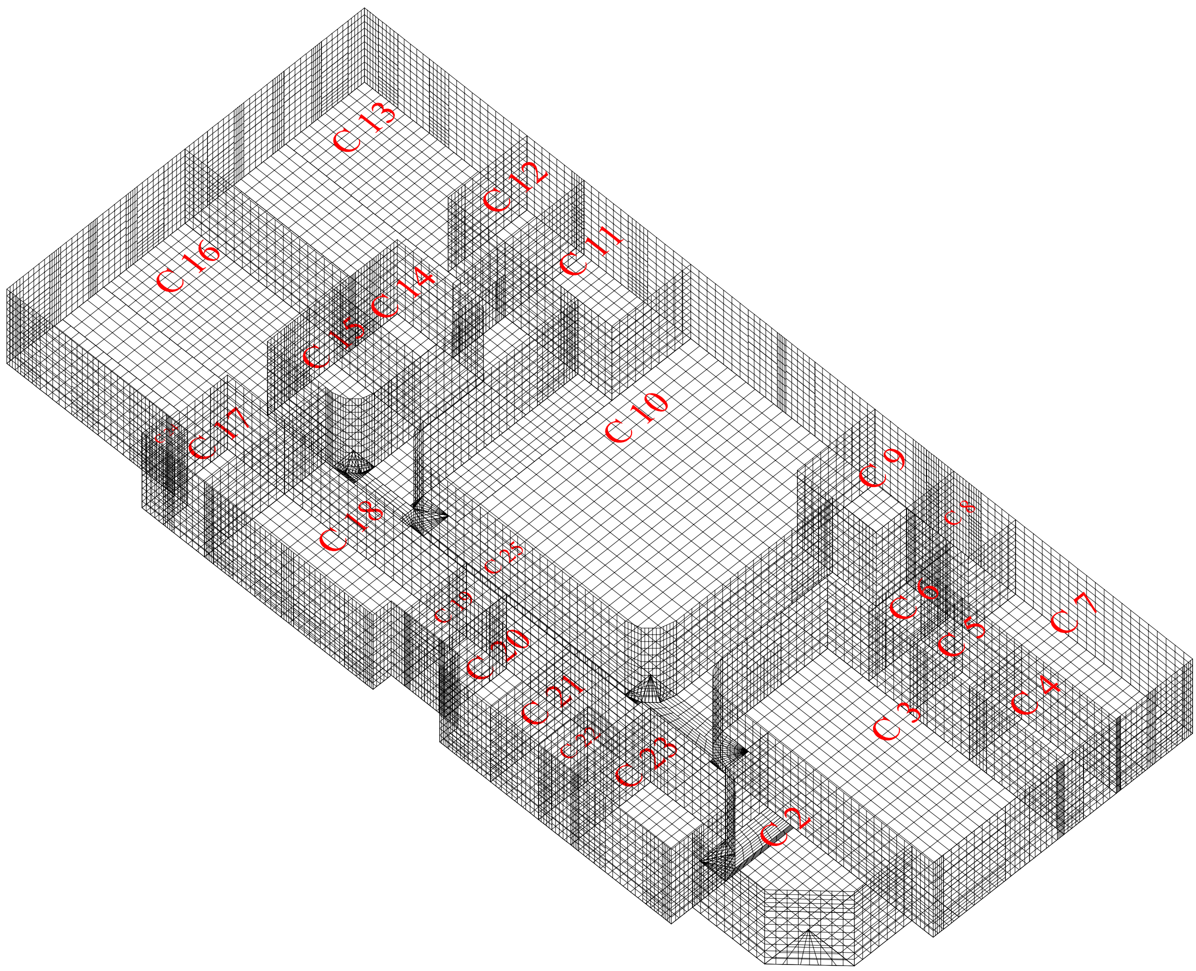


Figure 2. Identification of the indoor compartment of the kindergarten school building.

## 4.1 Input data

The input data in the software are:

- the buildings geometry (introduced in a three-dimensional design software);
- the boundary conditions;
- the materials thermal proprieties;
- the outdoor environmental and geographical conditions;
- the initial conditions;
- the several heat and mass load;
- the occupation cycle;
- the occupant's clothing level;
- the occupant's activity level;
- the air ventilation topologies.

The input data, associated to the building's geometry, were numerically used by the model in the development of an integral equations system.

The external environmental variables used as input data, namely the air temperature and air relative humidity, were experimentally measured in a Winter typical day, in 27th January 2007 (see Figure 3).

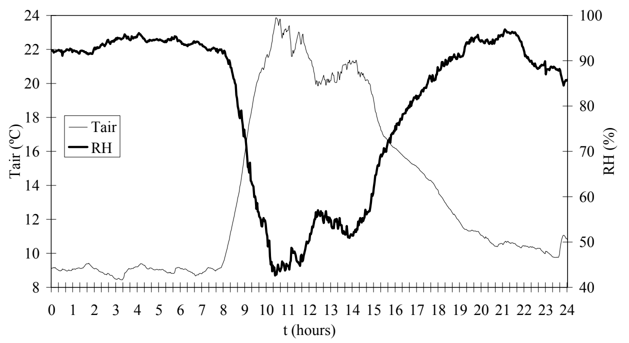


Figure 3. Air temperature ($T_{air}$) and air relative humidity (RH) evaluation used as input data.

## 4.1 Validation tests

The experimental data used in the numerical model validation of the indoor air temperatures for three occupied strategic rooms (numbers 3, 10 and 16) were measured in the typical Winter, the 27th January 2007. All measured data were stored in four dataloggers during 24 hours with an acquisition rate of 1 sample per minute.

The evolution of the measured and calculated indoor air temperature, presented in [15], was associated to compartment number 3, number 10 and number 16. Classroom number 3 is equipped with windows turned South, the playground number 10 is equipped with windows turned to East and classroom number 16 is equipped with windows turned West and North.
In accordance with the obtained results, it was possible to conclude that the numerical model reproduces the experimental indoor air temperatures behavior. In general, the difference between numerical and experimental indoor air temperature values is lower than 2.5 ºC.
Some discrepancies verified between the numerical values and the experimental results, are associated to:

- the North classroom windows curtains, that were partially closed during the experimental data assessment, creating an obstacle to the radiative exchanges, verified in the numerical over-dimensioned values for this classroom (compartments 16);
- the mean value for the air renovation experimentally obtained in some spaces, presents local differences;
- the building interior bodies, that can influence the building thermal inertia, were not considered;
- the ceiling, in contact with the outdoor environment, presents a great solar load. Thus, small discrepancies in the identification of the material are reflected in the indoor air temperature calculation;
- the small differences in the evaluation of the surrounding buildings external geometry, are reflected in the kindergarten school building external surfaces solar radiation;
- the grid generation is spaced 30 cm in both directions. The reduction of this distance, with consequently increase of the calculation time, allows better shading effects and solar radiation calculations;
- the numerical model used to determine the external solar radiation, with and without cloudy sky. In this simulation the best model for the analyzed day was used, nevertheless, these kinds of models may cause some errors in solar radiation calculations;
- the outdoor environmental variables, used as input data, measured in the outdoor environment, due to the building dimensions and complexity.

## 4.2 Thermal behavior without greenhouse

The evolution of indoor air temperature for the hall, corridors and playground area (compartments 2, 10 and 25), the classrooms (compartments 3, 13 and 16) and the offices (compartments 7, 11 and 23) are presented in [15].
In accordance with the obtained results was possible to conclude that:

- in occupied space, the classrooms with windows turned to North (compartments 13 and 16) had the lowest indoor air temperature values, while the hall (compartment 2) presented the highest indoor air temperature values;
- the hall, with high window area turned South and West, in accordance with the highest indoor air temperature verified, can be used as indoor greenhouse. The warm air can be used to heat the indoor air temperature of the classroom with windows turned North (compartments 13 and 16).

## 4.3 Thermal comfort without greenhouse

The evolution of thermal comfort levels for the hall, corridors and playground area (compartments 2, 10 and 25), the classrooms (compartments 3, 13 and 16) and the offices (compartments 7, 11 and 23) are presented in [15].
The PMV index is calculated, by the software, for each space, using the numerical values of the indoor air temperature, air velocity (obtained through the air renovation and recycled air mass flow), air relative humidity and mean radiant temperature (obtained through the mean value of the compartments surrounding surfaces temperatures), for a pre-defined clothing and activity level. In this calculus the Fanger model, presented in [2], is used. The PPD index is correlated with the PMV index using the Fanger model, presented in [2].
In accordance with the obtained results it's possible to conclude that:

- the hall is thermally uncomfortable, by positive PMV values, and the corridor and the playground are thermally comfortable in the afternoon;
- the classrooms with window turned North are most uncomfortable than the classroom with windows turned to South;
- the offices are thermally comfortable in the afternoon, nevertheless their occupation during the day isn't continuous.

## 4.4 Thermal behavior with greenhouse

After are identified the spaces more thermally uncomfortable in the simulation without greenhouse,

in this section is numerically implemented a greenhouse in the Kindergarten in the hall space. This greenhouse, that increases the air temperature level in Winter conditions using solar renewable energy, is used to warm the indoor air of the classrooms located in the North area of the kindergarten.
In this study it is analyzed in detail three situations: the greenhouse ventilation operating time (1) and the warm airflow transport way, using internal ducts system (2) or a corridor space (3), from the greenhouse to the indoor coldest spaces:

- in the first one is analyzed the ventilation operating works between 8 and 19 hours or between 9 and 19 hours. In this simulation is used one air renovation in the classrooms 13 and 16;
- in the second one the warm airflow transport using an internal ducts system with one or two air renovations in the classrooms 13 and 16;
- in the third one the warm airflow transport using an indoor corridor space with one or two air renovations in the classrooms 13 and 16.

The evolution of air temperature calculated inside compartments number 2, 13 and 16, with warm airflow transport using an indoor corridor space, without greenhouse and with greenhouse ventilation operating time between 8 and 19 hours and between 9 and 19 hours, with one air renovation in the classrooms 13 and 16, is presented respectively in figures 4, 5 and 6.

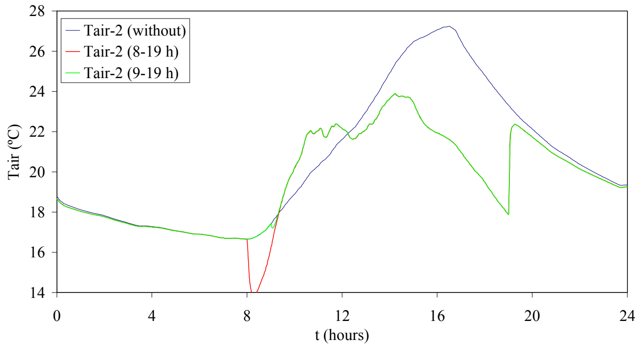


Figure 4. Evolution of air temperature calculated inside compartments number 2, without greenhouse and with greenhouse to work between 8 and 19 hours and between 9 and 19 hours (with warm airflow transport using an indoor corridor space).

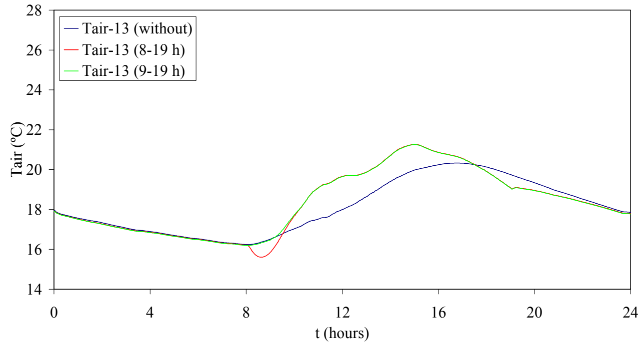


Figure 5. Evolution of air temperature calculated inside compartments number 13, without greenhouse and with greenhouse to work between 8 and 19 hours and between 9 and 19 hours (with warm airflow transport using an indoor corridor space).

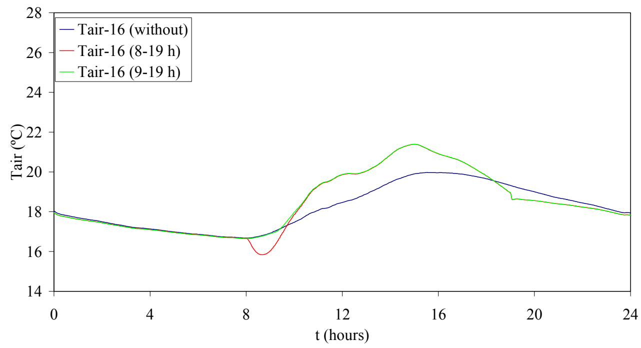


Figure 6. Evolution of air temperature calculated inside compartments number 16, without greenhouse and with greenhouse to work between 8 and 19 hours and between 9 and 19 hours (with warm airflow transport using an indoor corridor space).

In accordance with the obtained results it's possible to conclude that:

- is very important, for each kind of situation, to evaluate the time that the ventilation system works;
- in the actual situation, after being analyzed, is suggested that the ventilation system in the greenhouse stars operating at 9 hours and turns off at 19 hours.

The evolution of air temperature calculated inside compartments number 2, 13 and 16, with warm airflow transport using an internal ducts system, without greenhouse and with greenhouse with one and two air renovations in the classrooms 13 and 16, is presented respectively in figures 7, 8 and 9.

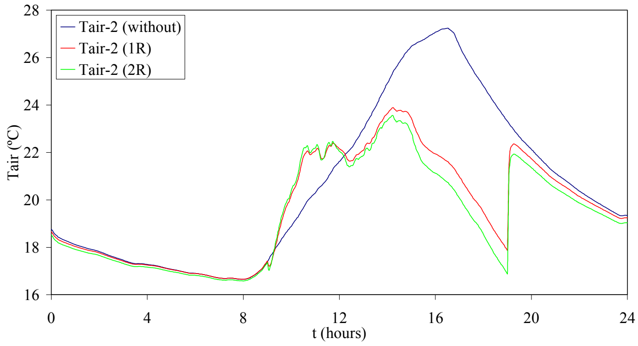


Figure 7. Evolution of air temperature calculated inside compartment number 2, without greenhouse and with greenhouse with one (1R) and two (2R) air renovations (warm airflow transport using an internal ducts system).

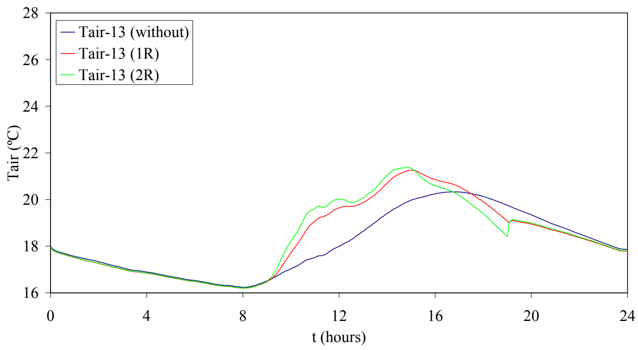


Figure 8. Evolution of air temperature calculated inside compartment number 13, without greenhouse and with greenhouse with one (1R) and two (2R) air renovations (warm airflow transport using an internal ducts system).

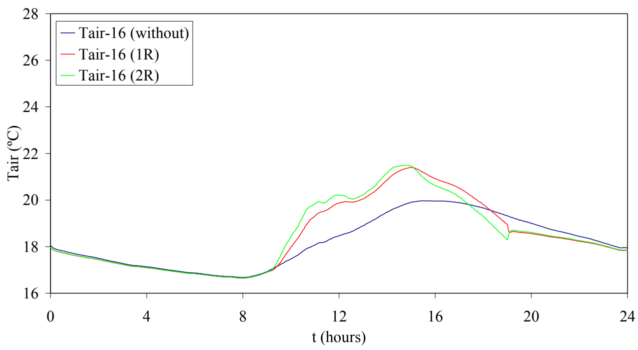


Figure 9. Evolution of air temperature calculated inside compartment number 16, without greenhouse and with greenhouse with one (1R) and two (2R) air renovations (warm airflow transport using an internal ducts system).

The evolution of air temperature calculated inside compartments number 2, 13, 16 and 25, with warm airflow transport using an indoor corridor space, without greenhouse and with greenhouse with one and two air renovations in the classrooms 13 and 16, is presented respectively in figures 10, 11, 12 and 13.

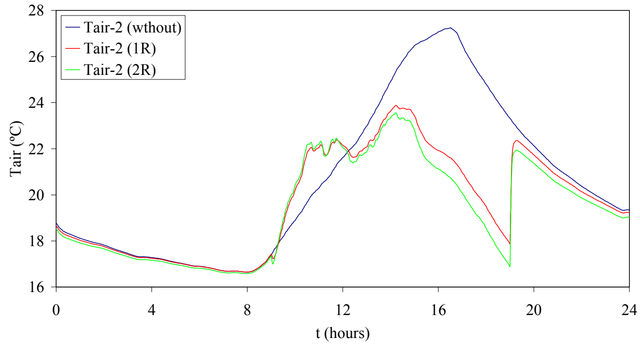


Figure 10. Evolution of air temperature calculated inside compartments number 2, without greenhouse and with greenhouse with one (1R) and two (2R) air renovations (warm airflow transport using an indoor corridor space).

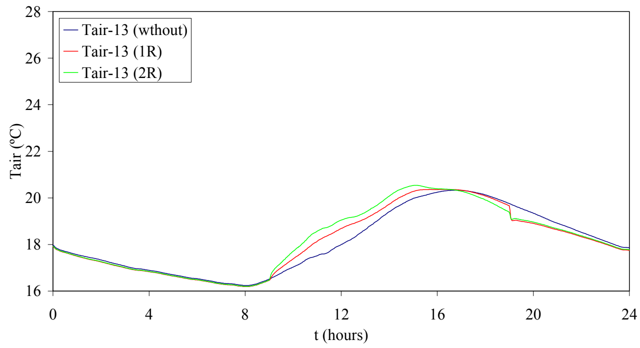


Figure 11. Evolution of air temperature calculated inside compartments number 13, without greenhouse and with greenhouse with one (1R) and two (2R) air renovations (warm airflow transport using an indoor corridor space).

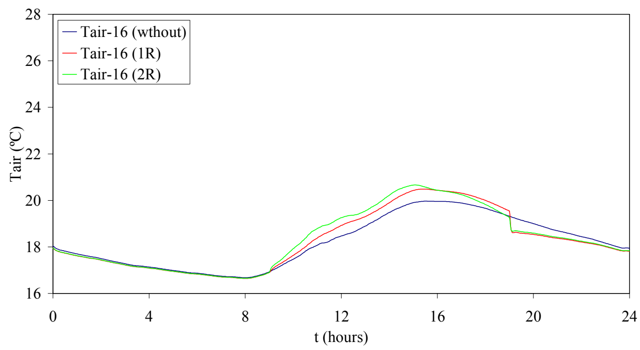


Figure 12. Evolution of air temperature calculated inside compartments number 16, without greenhouse and with greenhouse with one (1R) and two (2R) air renovations (warm airflow transport using an indoor corridor space).

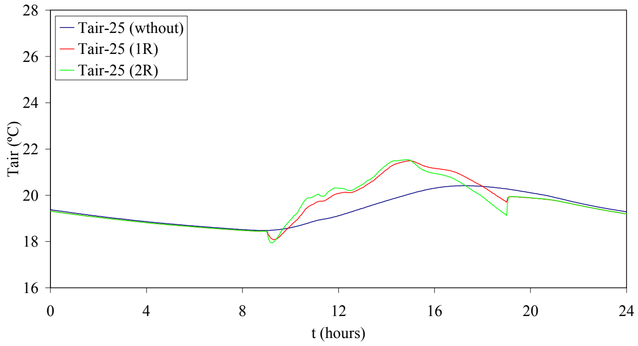


Figure 13. Evolution of air temperature calculated inside compartments number 25, without greenhouse and with greenhouse with one (1R) and two (2R) air renovations (warm airflow transport using an indoor corridor space).

In accordance with the obtained results it's possible to conclude that:

- one air renovation promotes higher air temperatures levels in the afternoon, while two air renovations promote higher air temperatures levels in the morning in classrooms 13 and 16;
- when the warm airflow transport using an indoor corridor space, the air temperature levels verified in the classrooms 13 and 16 are lightly lower than when the warm airflow transport using an internal ducts system;
- Nevertheless, to decide the best system to be used is important to analyze also the thermal comfort conditions and the investment needs to install the systems.

## 4.5 Thermal comfort with greenhouse

In this section the thermal comfort, which the occupants are subjected in the hall (number 2), playground (number 10), classrooms (numbers 3, 13 and 16) and corridor (number 25), is evaluated. In this study two situations are analyzed: warm airflow transport using an internal ducts system (1) or corridor space (2). In each situation one and two air renovations, in the classrooms 13 and 16, are used.

The evolution of PPD index, when one air renovation is transported by the ducts system, is presented from figures 14 to 15, while when two air renovations are transported by the ducts system, is presented from figures 16 to 17. In figures 14 and 16 are shown PPD index results of the classrooms (numbers 3, 13 and 16), while in figures 15 and 17 are shown PPD index results of the hall (number 2), playground (number 10) and corridors (number 25).

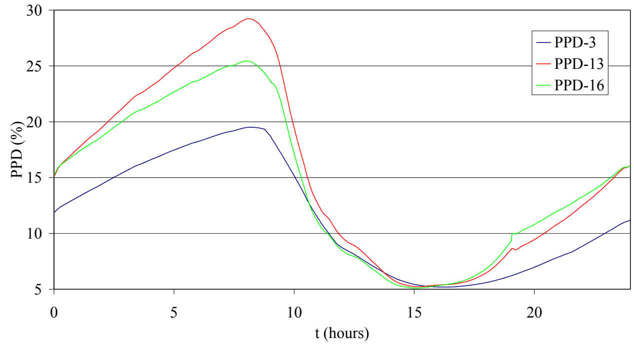


Figure 14. Evolution of PPD index calculated inside classrooms numbers 3, 13 and 16, when one air renovation is transported by the ducts system.

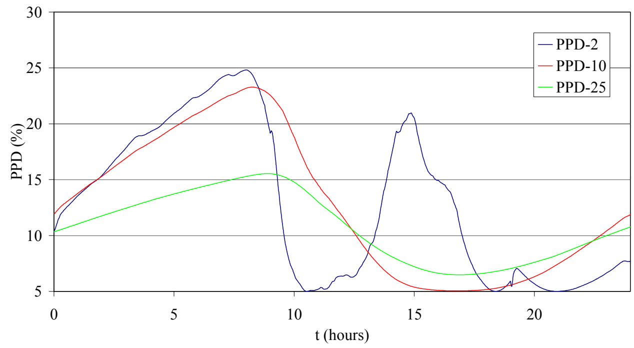


Figure 15. Evolution of PPD index calculated inside the compartments numbers 2 (hall), 10 (playground) and 25 (corridors), when one air renovation is transported by the ducts system.

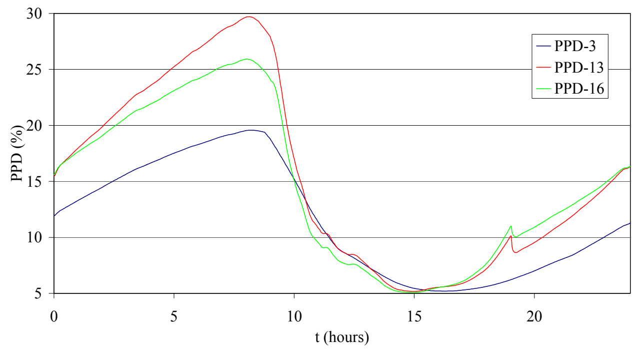


Figure 16. Evolution of PPD index calculated inside classrooms numbers 3, 13 and 16, when two air renovations are transported by the ducts system.

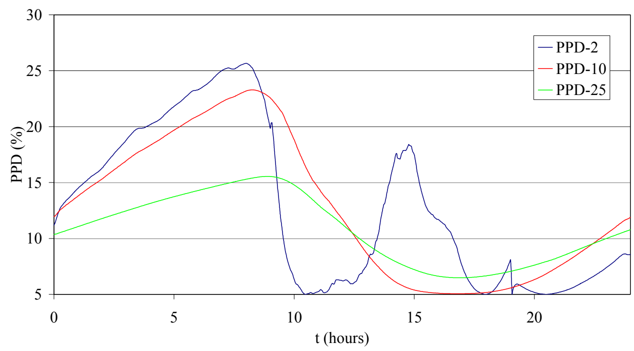

Figure 17. Evolution of PPD index calculated inside the compartments numbers 2 (hall), 10 (playground) and 25 (corridors), when two air renovations are transported by the ducts system.

The evolution of PPD index, when one air renovation is transported by the corridor space, is presented from figures 18 to 19, while when two air renovations are transported by the corridor space, is presented from figures 20 to 21. In figures 18 and 20 are shown PPD index results of the classrooms (numbers 3, 13 and 16), while in figures 19 and 21 are shown PPD index results of the hall (number 2), playground (number 10) and corridors (number 25).

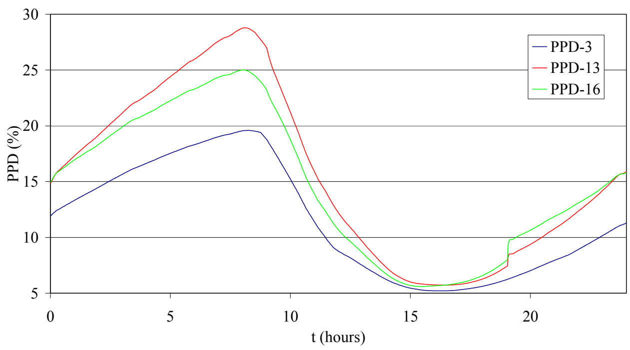


Figure 18. Evolution of PPD index calculated inside classrooms numbers 3, 13 and 16, when one air renovation is transported using the corridor space.

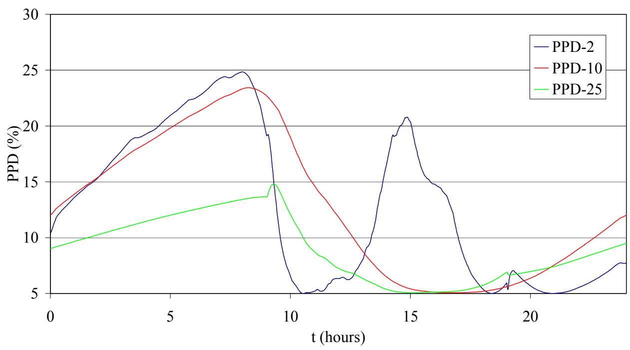


Figure 19. Evolution of PPD index calculated inside the compartments numbers 2 (hall), 10 (playground) and 25 (corridors), when one air renovation is transported using the corridor space.

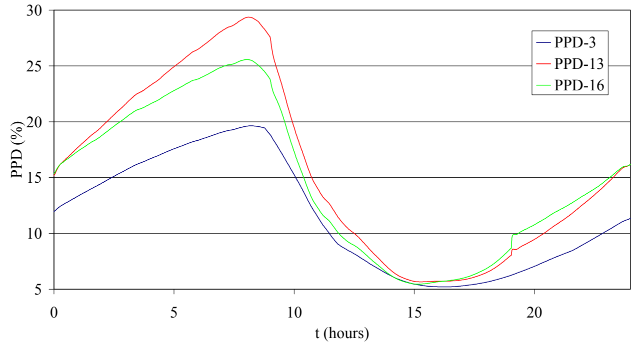


Figure 20. Evolution of PPD index calculated inside classrooms numbers 3, 13 and 16, when two air renovations are transported using the corridor space.

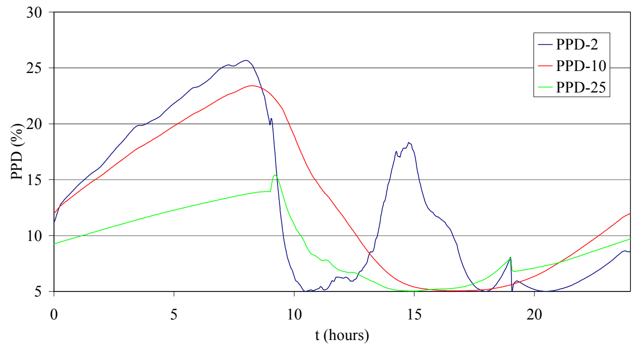


Figure 21. Evolution of PPD index calculated inside the compartments numbers 2 (hall), 10 (playground) and 25 (corridors), when two air renovations are transported using the corridor space.

In accordance with the obtained results it's possible to conclude that:

- one air renovation promotes better thermal comfort conditions in the afternoon, while two air renovations promote better thermal conditions in the morning;
- when the warm airflow transport using an indoor corridor space, the thermal comfort levels verified in the North classrooms are lightly lower than when the warm airflow transport using an internal ducts system. In general, the thermal comfort conditions are acceptable after the 10 hours in accord to the category C. When the warm airflow is transported in the ducts system the Category B is verified after the 11:30 hours, while when the warm airflow is transported in the corridor space the Category B is verified after the 12 hours;
- in the playground, in the lunch and afternoon snack time, the thermal comfort conditions are acceptable;
- the thermal comfort level in the corridor space is higher when the warm airflow is transported in the corridor space than when the warm airflow is transported in the ducts system;

- the thermal comfort level in the hall space when the warm airflow is transported in the ducts system is similar than when the warm airflow is transported in the corridor space. Nevertheless, when two air renovations are used the thermal comfort level in the hall is higher that when one air renovations is used in the classrooms 13 and 16.

# 5 Conclusions

In this work a numerical model, which simulates the buildings thermal response and evaluates the indoor environment comfort, in transient conditions, is used in the application of an indoor greenhouse in the energy and thermal comfort performance in a kindergarten school building, in the South of Portugal, in Winter conditions.

The work is divided in five parts: in the first one the numerical values are compared to the experimental measured data, in the second one the indoor temperature field is used to identify potential spaces used as indoor greenhouse with enough capacity to heating the air, in the third one the indoor thermal comfort level, using the PMV and PPD indexes, that occupants are subjected, in the fourth one the indoor temperature field using an indoor greenhouse with capacity to use the solar radiation in the indoor air heating and in the fifth one the indoor thermal comfort level, using an indoor greenhouse, that occupants are subjected, are evaluated. In the last two parts the greenhouse ventilation operating time and the warm airflow transport way, use an internal ducts system and a corridor space, from the greenhouse to the indoor coldest spaces, are analyzed.

The validation of the numerical model, being considered the kindergarten school building and the surrounding buildings, shows good agreement between the numerical values and the experimental data. The higher difference, in general, doesn't exceed the 2.5 ºC.

It was verified that the classrooms with windows turned North present the lowest indoor air temperature values, while the hall, with significant area of windows glasses turned South and West, the highest indoor air temperature values are present. The thermal comfort level verified in the classrooms with windows turned North is lower than in the classroom with windows turned South. Thus, is suggested to consider the hall as greenhouse used to warm the air to be used in the classrooms with windows turned North.

It is analyzed in detail the greenhouse ventilation operating time and the warm airflow transport way, using an internal ducts system or a corridor space, from the greenhouse to the indoor coldest spaces.

It was verified that in the actual system, after being analyzed, is suggested that the ventilation system in the greenhouse is on at 9 hours and off at 19 hours.

Finally, as the thermal comfort levels in the classrooms 13 and 16 are acceptable in the end of the morning and in the afternoon when the warm airflow is transported in the ducts system and in corridor space, as the thermal comfort level in the corridor is highest when the warm airflow is transported in the corridor space and as the total investment is lowest when the warm airflow is transported in the corridor space, is suggested, in this work, to use the corridor to transport the warm air from the hall to the North classrooms. As high air renovation promote highest thermal comfort levels in the morning in the North classrooms, in the corridor and in the hall, is suggested for example, in this work, to use two air renovations in the classrooms 13 and 16.

# 6 Acknowledgement

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