Development and implementation of high density occupied spaces grid generation with complex geometry used in thermal acoustical study

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ABSTRACT

In this study an integrated software, that is used in the evaluation of thermal acoustic phenomena in high density occupied spaces with complex geometry, as sitting rooms, classrooms, auditoriums, is made.
In the thermal component the software evaluates the internal airflow and the occupants' thermo-physiology, and in the acoustical component the software evaluates the direct and indirect sound.
In this paper the grid generation theory of a space with high occupation is made. The surrounding space surfaces and the external occupants' surfaces geometry, using geometric equations, are applied. The space geometry and, in special, the occupants' geometry grid generation around the body, are presented. The software develops three grid generations: one to the Computational Fluids Dynamics, other to the radiative heat exchanges and another to the Sound Propagation.
In the application, the space geometry is made using a computer aid design, while the occupants' are made using geometry equations. In this preliminary study, after being presented the grid generation details, sitting room internal thermal airflow field, the occupants' thermal distribution and the space reverberation time is also evaluated and discussed.

Keywords: Buildings Acoustical Modeling, Prediction and Simulation, Computer Software Programs.

1. INTRODUCTION

The integral evaluation of buildings or vehicles occupants' comfort was developed during several years. Acoustics, thermal, vibrations, indoor air quality and other topics were analyzed previously, as example, by Silva (1) and Conceição and Lúcio (2).

In the first one, Silva (1), in the case of passengers in vehicles, the evaluation of thermal environment and indoor air quality was evaluated. In this study the main topics considered are the temperature, air quality, noise, vibration, lighting and ergonomics.

In Conceição and Lúcio (2) two numerical models that simulate the human body biomechanical and the occupant thermal responses were presented. The first model is used in the vibration in the human body with stimuli in the feet and hands, while in the second model is used the evaluation of local thermal discomfort level, that an occupant feels, when is subjected to a turbulent airflow. These models, that work in transient conditions, evaluate the vibrations in different human body sections and the thermal sensation level that an occupant is subjected inside a compartment with non-uniform environmental conditions. The integration of the equation system, used in the models, is performed by a Runge-Kutta-Fehlberg method with error control.

In this paper the thermal acoustic topic, that involves the thermal component and the acoustic component, is analyzed in detail. The grid generation, used to obtain the thermal acoustic evaluation

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and an application example, using a space with high occupation level, is made.

The thermal component, that involves the airflow topology and the occupant thermo-physiology, was developed by several authors. Conceição et al. (3, 4) developed one software that simulates turbulent airflow inside a space and around the occupants, while Conceição et al. (5, 6, 7) developed a numerical software that simulates the Human Thermal Response and evaluates the human thermal comfort and the human thermal discomfort levels.

The sound propagation, in indoor spaces, is function not only the internal geometry, but also the internal temperature level. The evaluation of sound propagation can be made numerically or experimentally. However, in this paper only the numerical component is developed (see also 8, 9, 10, 11, 12, 13).

In the numerical software, using a coupling of three numerical models is important to consider all physical spaces and physical phenomena details. The physic space is guaranteed using the grid generation, while the thermal and acoustical physical phenomena are obtained using numerical equations.

In the surrounding and internal geometry, related with the physical domain, are considered all internal bodies and the internal occupants. The internal bodies, seat, tables, ducts and other details are considered.

The internal air temperature field, that is used to evaluate the occupants' comfort and influences the sound propagation, is function to the internal surfaces temperature and internal airflow. The internal surfaces temperature are function to the internal air temperature (convection) and the heat exchanges by radiation to the other surrounding surfaces, while the internal airflow is function to the internal surfaces, as occupants, seat, table and other interior bodies, and the internal air renovation.

Thus, in order to evaluate the thermal acoustic phenomena that the occupants are subjected is important to evaluate the occupants' thermal phenomena, the internal airflow and the sound propagation. In order to evaluate these three phenomena is important to evaluate three grid generation: one for the occupants' thermal response, used to evaluate the thermal comfort level (14), other for the internal airflow, used to evaluate the Draught Risk and indoor air quality (14), and other for the internal acoustics, used to evaluate the reverberation time (15).

2. NUMERICAL MODEL

2.1 Integral and Differential Coupling Numerical Model

In this paper the integral and differential coupling numerical models are developed and applied. In the integral numerical models the Human Thermal Response and Sound Propagation are used, while in the differential numerical model the Computational Fluids Dynamics is used.

The Computational Fluids Dynamics numerical model evaluates the environmental thermal variables around the occupants and these variables are used as input data in the human thermal comfort numerical model. The Human Thermal Response numerical model evaluated the occupants and clothing thermal variables and these variables are used as input data in the Computational Fluids Dynamics numerical model. In the numerical simulation these two numerical models are applied and used an iterative method. The Sound Propagation numerical model uses the air temperature level, inside the experimental chamber and around the senior occupants, calculated by the Computational Fluids Dynamics numerical model, in the sound velocity propagation evaluation.

2.2 Computational Fluids Dynamics

The Computational Fluids Dynamics numerical model evaluates the air temperature, air velocity and carbon dioxide concentration around the occupant. This numerical model is based in Navier-Stokes differential equations in Cartesian coordinates and works in steady-state conditions and in non-isothermal conditions. In the turbulence simulation, in accordance with Conceição et al (3, 4), is applied the RNG model. This numerical model evaluates the airflow around the occupants, the draught risk (based in empirical models) and the air quality level.

2.3 Human Thermal Response

The Human Thermal Response numerical model evaluates the body temperature, the clothing temperature, the skin water vapor, the clothing water vapor and the thermal comfort level. The Human Thermal Response numerical model, in accordance with Conceição et al (5, 6, 7), based in mass and energy integral equations, works in transient conditions and simulates simultaneously a group of persons. The body is divided in 24 cylindrical and 1 spherical elements. Each element is divided in core, muscle, fat and skin layers and could be protected from external environment using clothing layers.

2.4 Sound Propagation

The integral Sound Propagation numerical model is based in geometric methods and mathematic numerical models. The acoustical geometric methods developed graphically the path between the source and the receiver, considering the multi reflections, diffractions and refractions at surfaces of the occupied room, using an image source method. This ray tracing method find the reverberation paths between the source and the receiver. This numerical model, between other variables, in this work, is used to evaluate the reverberation time.

3. GRID GENERATION

3.1 Case Studied

In this study simulations are performed, in summer conditions, in a virtual chamber with dimensions of 4.50×2.55×2,50 m^3, equipped with 2 tables, 16 chairs, 2 exhaust diffusers, 4 vertical inlet ducts and 8 horizontal transport ducts. The virtual chamber has an occupancy of 16 senior people.

In the exhaust diffusers are considered two air ducts, located the 1.70 m from the ground, connected to the ceiling and centred for each tables. This philosophy improves the thermal comfort and air quality and reduces the risk of disease transmission.

The vertical ducts systems are equipped with consecutive holes, that promote horizontal jets at low air velocity, in order to promote low Draught Risk. The four vertical ducts are located in the corners of the compartment with 0.15 m in diameter and promote the airflow near the walls. The holes are placed from a height of 0.15 m to 1.70 m, width a diameter 0.05 m. The horizontal ducts are located on the floor and on the ceiling of the chamber, and are used to transport the airflow to the vertical ducts.

In this simulation the external air temperature is 28 ºC, the inlet air temperature is 25 ºC, the renovation airflow is 0,16 m^3/s and the cooling power is 477,75 W. In the numerical sound propagation simulation the surface absorption coefficient 20 % is considered.

In this numerical simulation, with 1.2 met. of activity level and 0.5 clo. (short-sleeved shirt, shorts and shoes) of clothing level, are evaluate the air velocity flow, air temperature flow, skin and clothing human body temperature, thermal comfort level and reverberation time.

3.2 Computational Fluids Dynamics

The Computational Fluids Dynamics numerical model is based in boxes with 5 cm of dimension. In the present situation a grid box is made by 90×51×50 units, with a total of 229500 boxes. The boxes input, related interior bodies, like tables, desks, vertical ventilation ducts systems and horizontal ducts, is made using a computer aid design software, while the occupants' presence is made numerically using equations after an occupant location is identified.

In figure 1 is presented the grid generation used in the Computational Fluids Dynamics, while in figures 2 and 3 are presented the details of indoor bodies and occupants. Figure 2 presents the details of the grid generation in one of the two desks occupied by eight seniors used in the Computational Fluids Dynamics, while in figure 3 is presented the details of the grid generation in the desk a), seat b) and occupants c) used in the Computational Fluids Dynamics.

The boundary elements used in the Human Thermal Response numerical model and in the Sound Propagation numerical model is build using the Computational Fluids Dynamics numerical model. In the first one only the interior bodies, like desks, seats, vertical ventilation ducts systems and horizontal ducts are developed, while in the second one the desks, seats, vertical ventilation ducts systems, horizontal ducts and occupants are developed. In the first one also the seniors' locations are necessary to export.

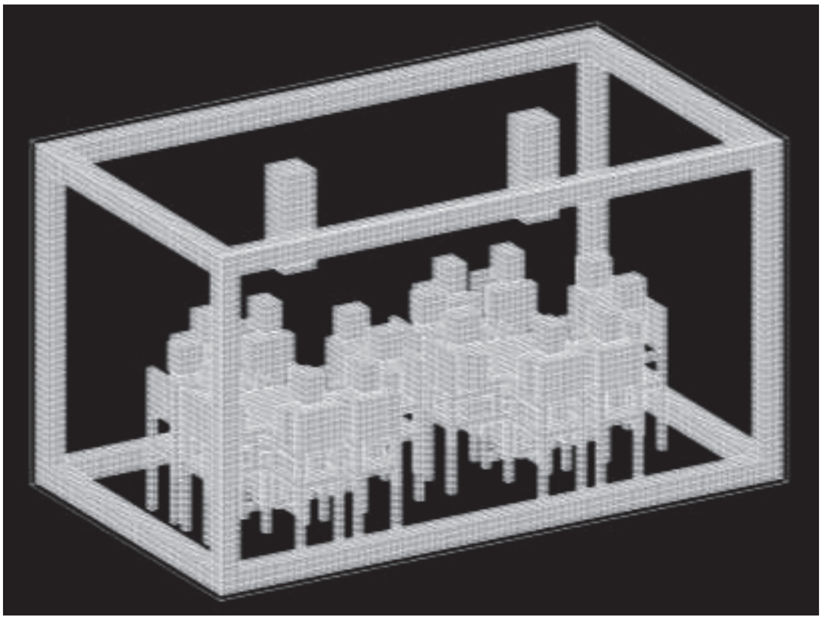


Figure 1 – Grid generation in the sitting room occupied by the 16 seniors used in the Computational Fluids Dynamics.

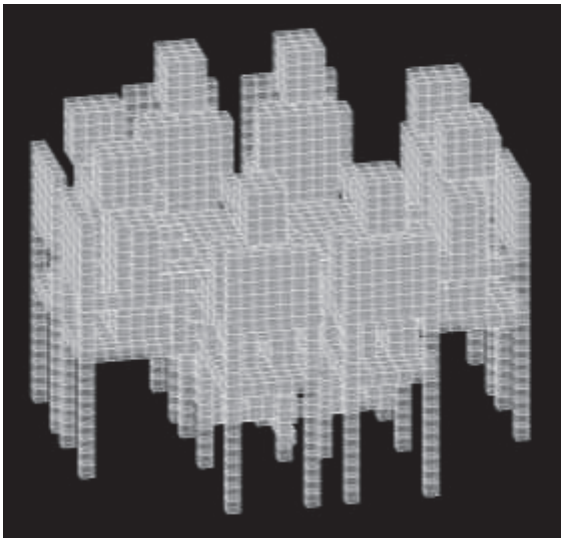
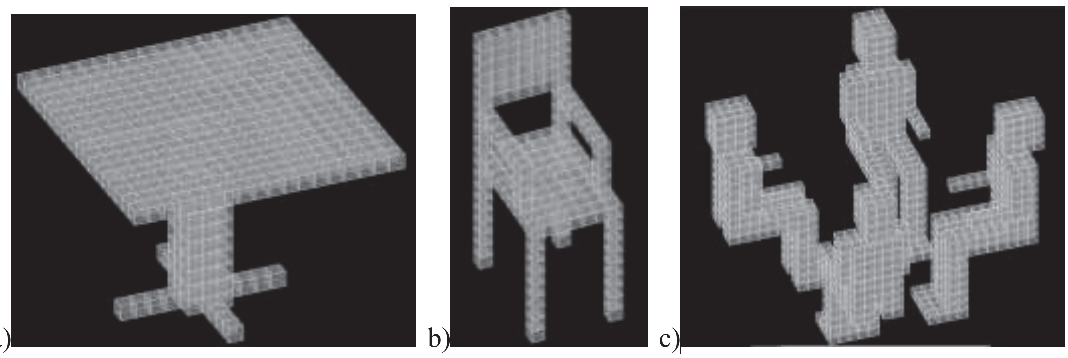


Figure 2 – Details of the grid generation in the one of the two desks occupied by eight seniors used in the Computational Fluids Dynamics.



a) b) c)

Figure 3 – Details of the grid generation in the desk a), seat b) and occupants c) used in the Computational Fluids Dynamics.

3.3 Human Thermal Response (HTR)

In the Human Thermal Response numerical model the grid generation is based in surfaces. The boundary element surfaces, namely the interior bodies like desks, seats, vertical ventilation ducts systems and horizontal ducts are exported from the Computational Fluids Dynamics numerical model. The grid generation, developed inside all the boundary elements, is used to evaluate the heat exchanges between the occupants and the surrounding surfaces and the incident solar radiation. The grid generation around the occupants, using cylinders and sphere, with the location exported from the Computational Fluids Dynamics, is promoted using geometric equations. In these simulations are considered 34428 boundary surfaces and in the 16 occupants, divided in 25 elements, are considered 64 boundary elements (total of 25600 boundary elements).

In figure 4 the boundary elements mesh in the sitting room occupied by the 16 seniors used in the Human Thermal Response is present, in figure 5 the boundary element mesh in the one of the two desks occupied by eight seniors used in the Human Thermal Response is shown, while in figure 6 the boundary element mesh in the desk and in the occupants, used in the Human Thermal Response, is presented.

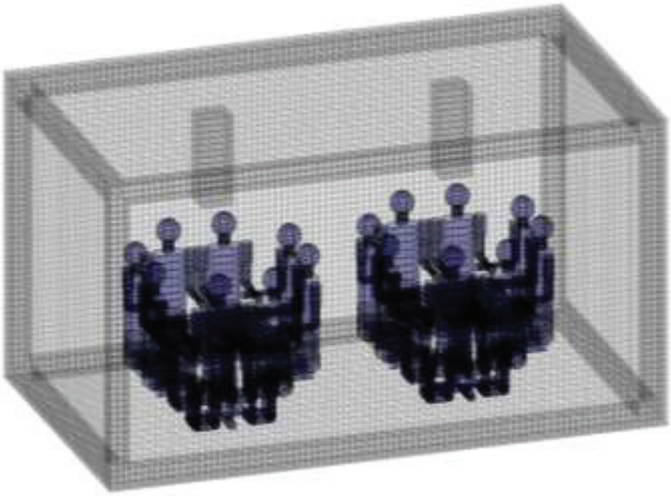
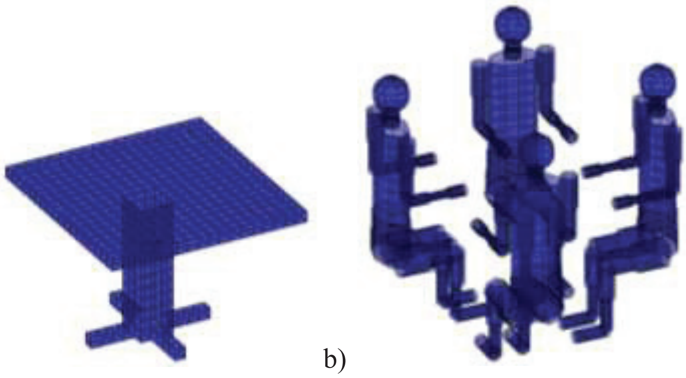


Figure 4 – Boundary elements mesh in the sitting room occupied by the 16 seniors used in the Human Thermal Response.

Figure 5 – Boundary elements mesh in the one of the two desks occupied by eight seniors used in the Human Thermal Response.



a) b)

Figure 6 – Boundary elements mesh in the desk a) and occupants b) used in the Human Thermal Response.

3.4 Sound Propagation (SP)

The Sound Propagation numerical model grid generation is based in surfaces. The boundary elements surfaces, namely the interior bodies like desks, seats, vertical ventilation ducts systems, horizontal ducts and occupants are exported from the Computational Fluids Dynamics numerical model. The Sound Propagation numerical model, before calculate the sound path, group the boundary elements surfaces in order to obtain a simplified geometrical model. In the present situations, using boundary surfaces, are considered 2332 boundary elements surfaces.

Figure 7 show the boundary elements mesh in the sitting room occupied by the 16 seniors used in the sound propagation, figure 8 presents the boundary elements mesh in one of the two desks occupied by eight seniors used in the sound propagation and the figure 9 show the boundary elements mesh in the desk, seat and seniors used in the sound propagation.

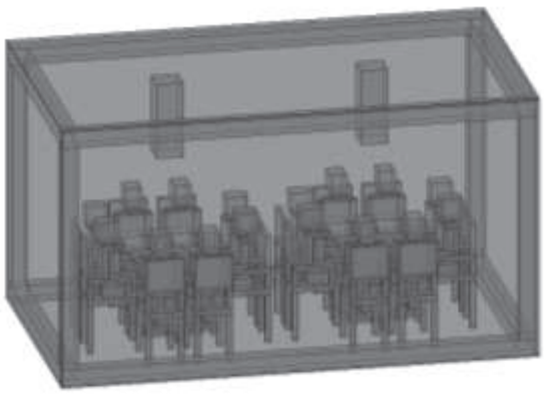


Figure 7 – Boundary elements mesh in the sitting room occupied by the 16 seniors used in the Sound Propagation.

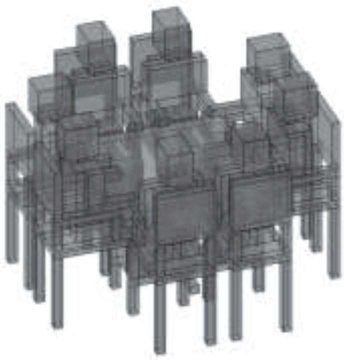
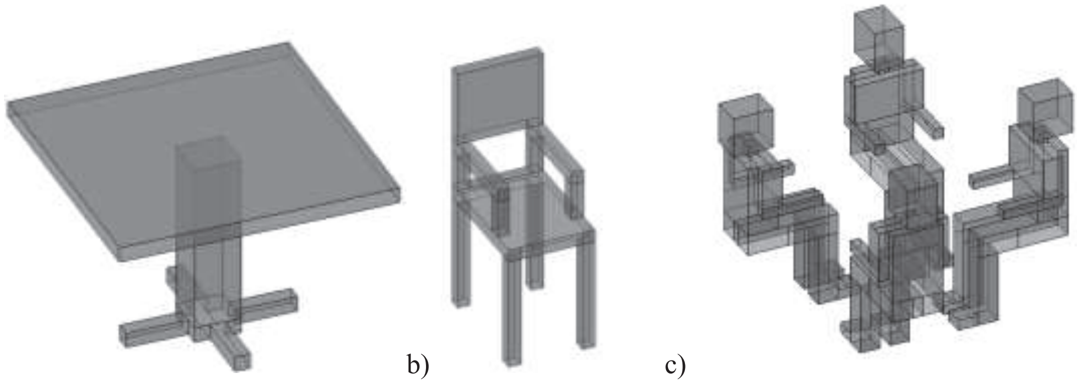


Figure 8 – Boundary Elements mesh in one of the two desks occupied by eight seniors used in the Sound Propagation.



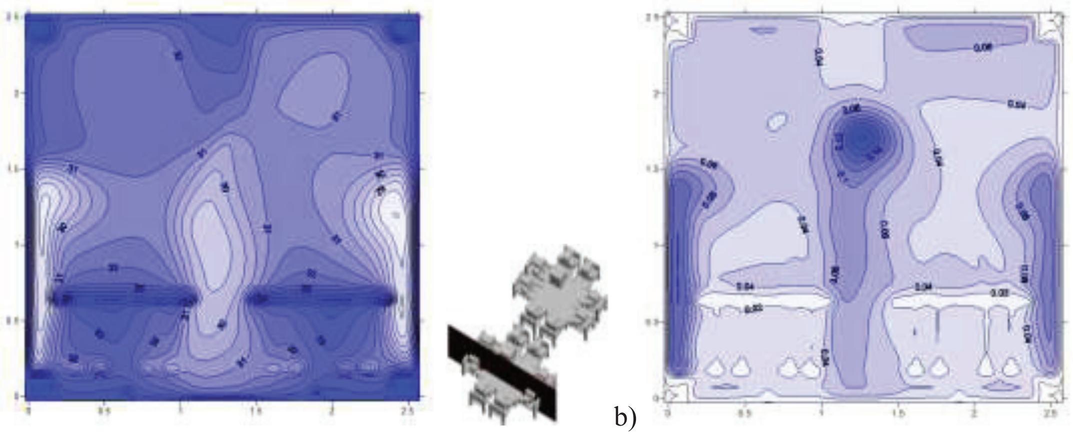
a) b) c)

Figure 9 – Boundary Elements mesh in the desk a), seat b) and seniors c) used in the Sound Propagation.

4. RESULTS AND DISCUSSION

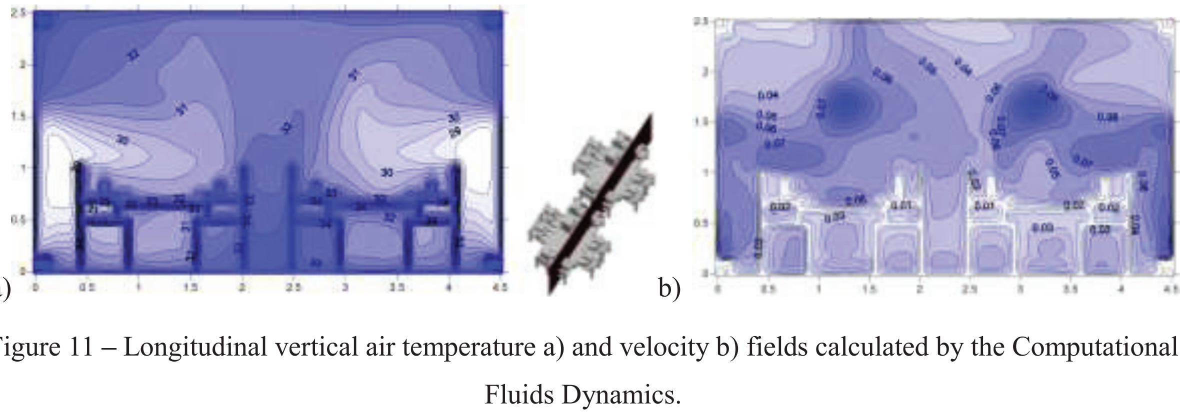
4.1 Computational Fluids Dynamics

Figure 10 shows the transversal vertical air temperature and velocity fields calculated by the Computational Fluids Dynamics and figure 11 shows the longitudinal vertical air temperature and velocity fields calculated by the Computational Fluids Dynamics. The figures a) are associated with the air temperature level, while figures b) are associated with the air velocity level.



a) b)

Figure 10 – Transversal vertical air temperature a) and velocity b) fields calculated by the Computational Fluids Dynamics.



a) b)

Figure 11 – Longitudinal vertical air temperature a) and velocity b) fields calculated by the Computational Fluids Dynamics.

In accordance with the obtained results, the air temperature presents highest values around the occupation and in the wall area. The air velocity is highest in the inlet and wall area and lowest and relatively uniform in the occupied area.

4.2 Human Thermal Response

In figure 12 is presented the distribution of skin temperature around the 16 seniors and in figure 13 is presented the distribution of clothing temperature around the 16 seniors, calculated by the Human Thermal Response numerical model.

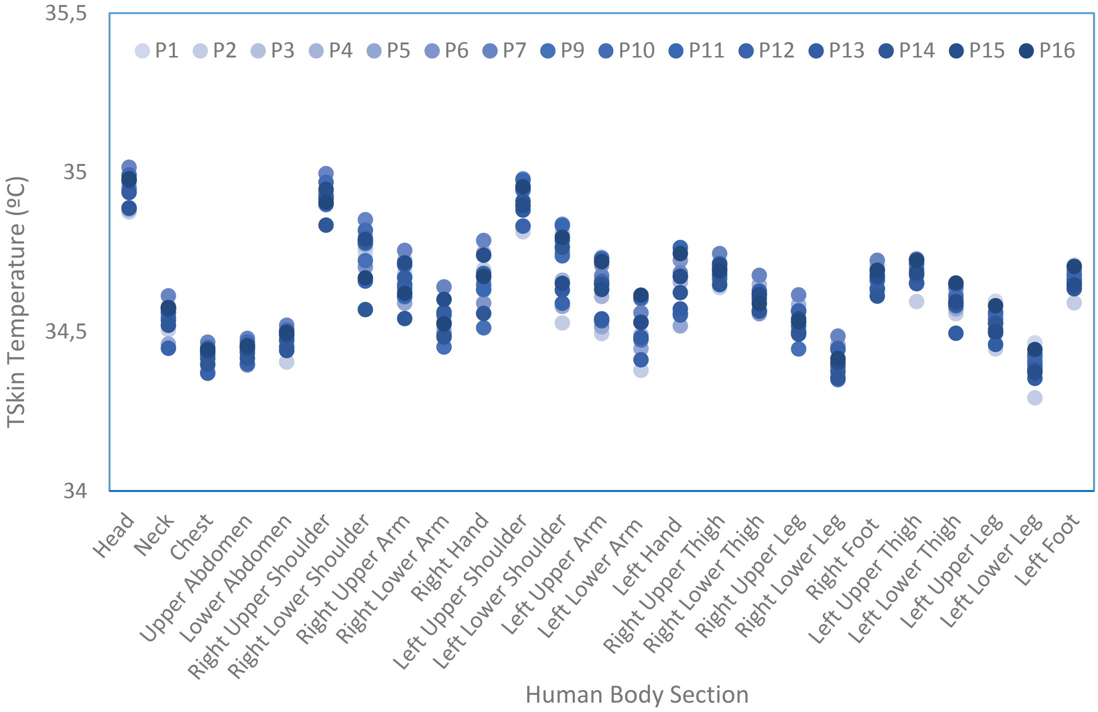


Figure 12 – Distribution of skin temperature around the 16 seniors' sections.

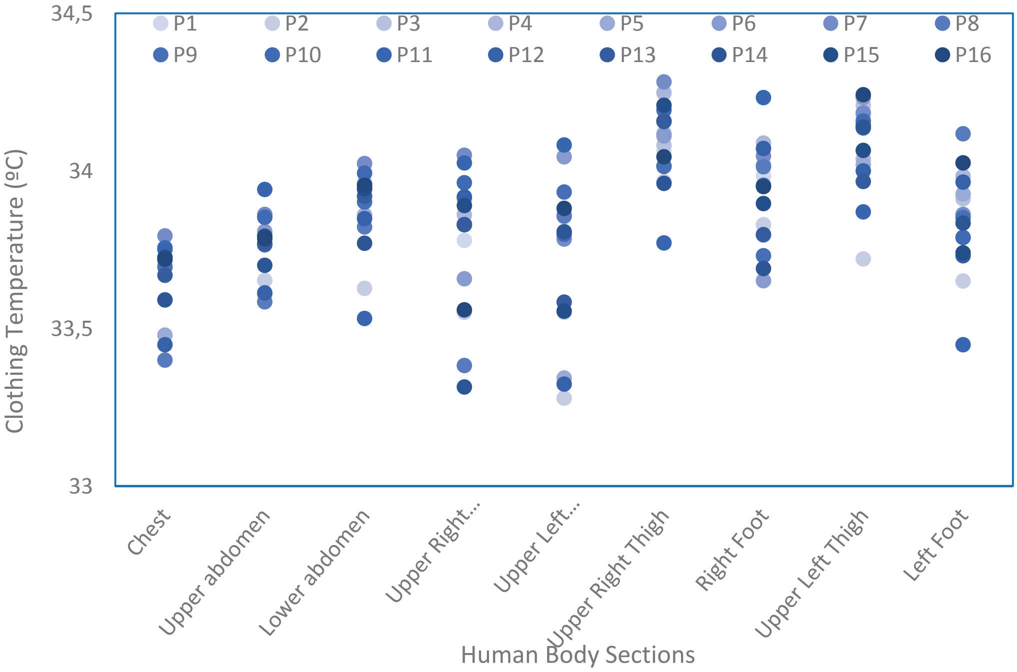


Figure 13 – Distribution of clothing temperature around the 16 seniors' sections.

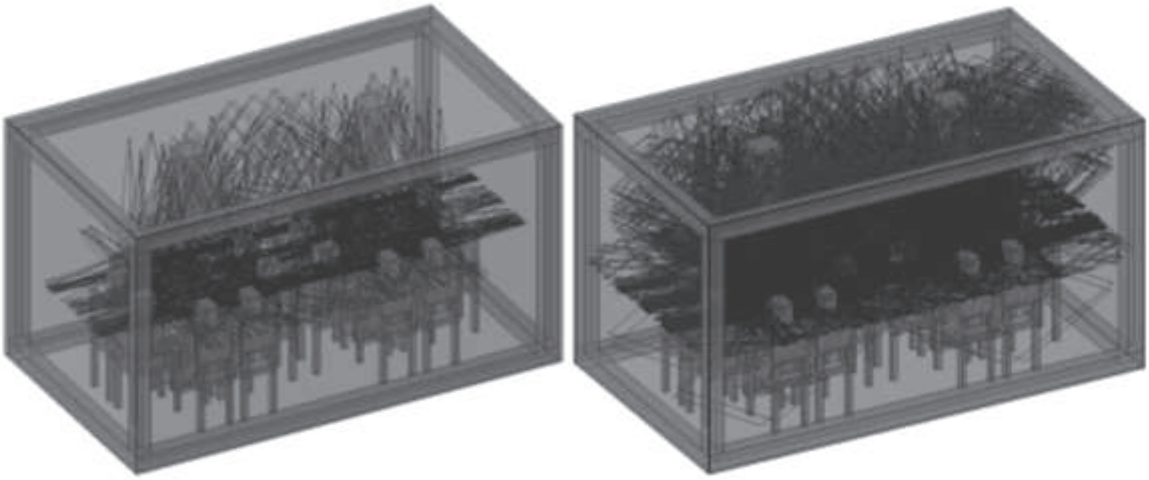
The clothed senior body section presents higher skin temperature levels. The clothing level temperature is higher in the lower body seniors section than in the upper body seniors section. The clothing temperature level is lower than the skin temperature level.

The mean Predicted Percentage of Discomfort, by warm thermal conditions, that the occupants are subjected, is 65.27 %. This value, in accordance with the obtained values, change between 64.32 % and 66.55 %. Thus, this ventilation system guarantees, in accordance with the obtained results, uniform thermal conditions to the occupants.

4.3 Sound propagation

In the sound propagation, presented in this section, is considered a sound impulse in the source and the monitoring in the receiver. As source was considered the mouth of the 16 seniors occupants, while as receiver as considered the right and left ear of the 16 seniors occupants.

Figure 14 show the sound propagation paths from a source to a receiver. The figure a) represents the direct and first reflections path, while the figure b) represents the direct, first and second reflections paths. In the figure 14 a) are presented 1013 paths and in the figure 14 b) are presented 3357 paths.



a) b)

Figure 14 – Sound propagation paths from a source to a receiver. Direct and first reflections paths a) and direct, first and second reflections paths b).

In figure 15, as example, is presented the philosophy used in the calculation of the reverberation time, when the source is located in the senior occupant (5) mouth (occupant seated in the first table and located between the two tables) and the receiver is located in the senior occupant (6) ears (occupant seated in the first table and located between the two tables). The two occupants are seated side by side.

The reverberation time is calculated numerically using a regression of the sound intensity level evolution, using an exponential equation, when the receiver is located in the left and right ears. Thus, the reverberation time is calculated, for the left and right ears, using the necessary time to decay 60 dB from the beginning of the test.

In figure 16 the reverberation time calculation when the source is located in the mouth of 16 occupants and the receiver is located in the ears of other 15 occupants are presented. The figure a) is associated to the receiver located in the left ear, while the figure a) is associated to the receiver located in the right ear.

The calculated reverberation time changes slightly during the occupation space and changes with the considered source and receiver. The calculated reverberation time changes between 0,028865 s and 0,79383 s, for the left ear, and changes between 0,028067 s and 0,78634 s, for the right ear. The mean reverberation time for the left ear is 0,53223 s, while for the right ear is 0,53289 s.

In accordance with (15) the suggested reverberation time, used as reference a furnished and non-occupied school space, is lower than 0,454s.

The calculated reverberation time is near the suggested value, however, in order to improve the calculated value is suggested to consider more reflection path in the simulation.

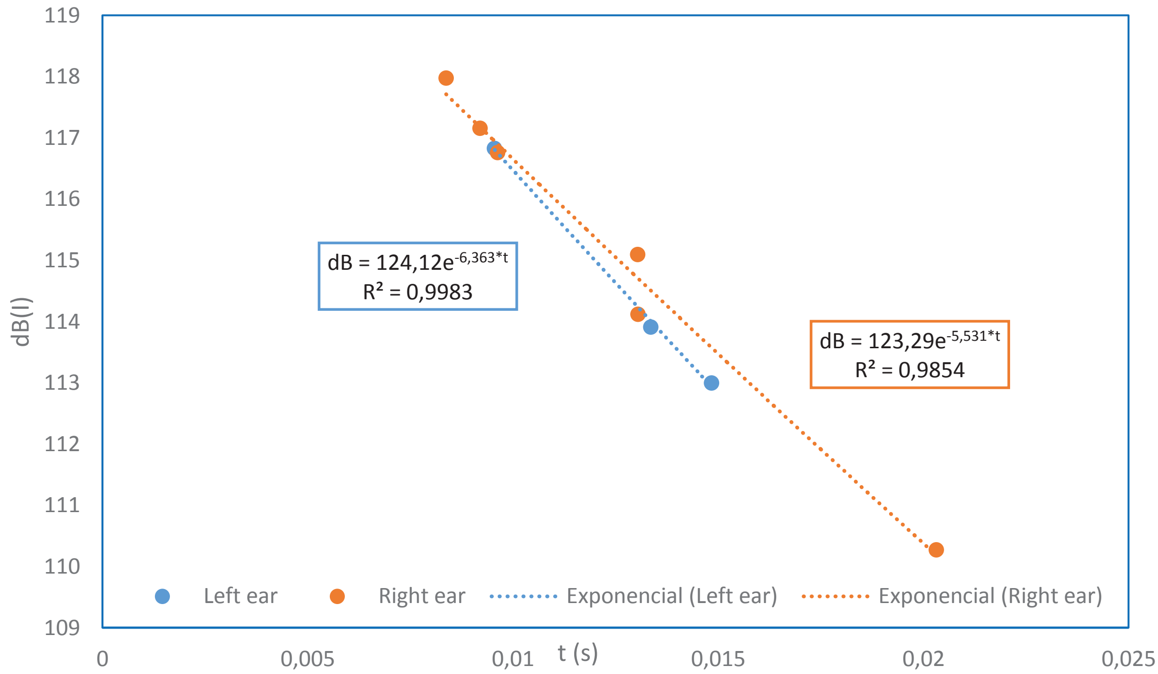


Figure 15 – Regression of the sound intensity level evolution when the source is located in the mouth of an occupant and the receiver is located in the left and right ears of other occupant.

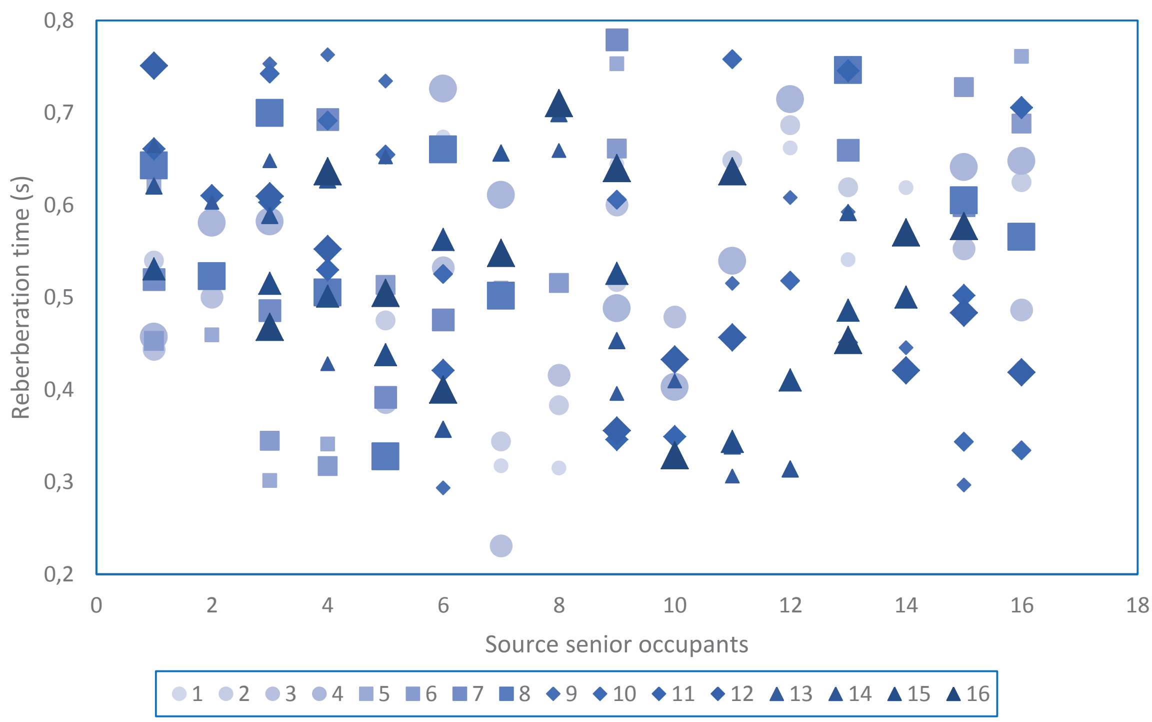


Figure 16a – Reverberation time calculation when the source is located in the mouth of 16 occupants and the receiver is located in the left a) and right b) ears of other 15 occupants.

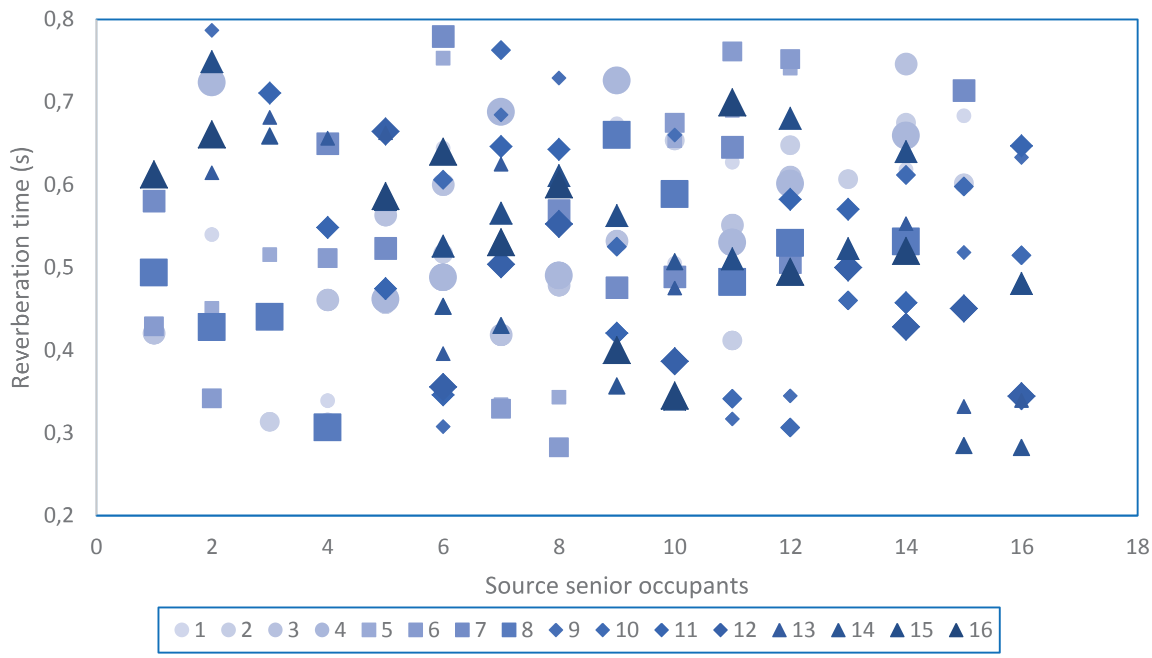


Figure 16b – Reverberation time calculation when the source is located in the mouth of 16 occupants and the receiver is located in the left a) and right b) ears of other 15 occupants.

5. CONCLUSIONS

In this study an integrated software, that is used in the evaluation of thermal acoustic phenomena in high density occupied spaces with complex geometry, as sitting rooms, classrooms, auditoriums, is made. In the application, the surrounding space and indoor geometry is made using the computer aid design, while the occupants' are made using geometry equations. In this preliminary study, after being presented the grid generation details, sitting room internal thermal airflow field, the occupants' thermal distribution and the space reverberation time is evaluated.

The numerical simulation is made in a virtual chamber, equipped with 2 tables, 16 chairs, 2 exhaust diffusers, 4 vertical inlet ducts and 8 horizontal transport ducts. The virtual chamber has an occupancy of 16 senior people and the simulation is made in summer conditions.

This ventilation system guarantees a low and uniform air velocity field in the occupation area and a highest air velocity field in the wall and outlet area, where no occupation is verified. The air temperature is lower in the occupation area than in the surrounding wall surface area.

In accordance with the temperature field obtained, the non-clothed senior body sections present higher skin temperature values than the clothed senior body sections temperature and this ventilation system guarantees, in general, uniform thermal conditions to the occupants.

In the reverberation time the direct, first and second reflections, with 3357 paths, are considered. The reverberation time is calculated numerically using an exponential equation regression of the sound intensity level evolution, when the source is located in the mouth and the receiver is located in the left and right ears. Thus, the reverberation time is calculated, for the left and right ears, using the necessary time to decay of 60 dB from the beginning of the test. Thus, the calculated reverberation time changes between 0,028067 s and 0,79383 s. The mean calculation reverberation time for the left ear is 0,53223 s and for the right ear is 0,53289 s, while the standard suggested reverberation time is lower than 0,454 s.

In order to increase the thermal comfort level and to reduce the air temperature level is suggested to reduce the inlet air temperature level or to increase the renovation airflow rate. And, in order to improve the calculated reverberation time value, is suggested to consider more reflection, as example, the third or fourth order, in the numerical simulation.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

1 - Silva MCG. Measurements of Comfort in Vehicles, review article, Measurements in Science and Technology 13 (2002) R41-R60.

2 - Conceição EZE, Lúcio MªMJR. Human Body Biomechanical and Thermal Response Models. Proc INTER-NOISE 2004; 22 - 25 August de 2004; Czech Republic, Prague 2004. The 33rd International Congress and Exposition on Noise Control Engineering.

3 - Conceição EZE, Lúcio MªMJR, Awbi HB. Comfort and airflow evaluation in spaces equipped with mixing ventilation and cold radiant floor. Building Simulation, March 2013, Volume 6, Issue 1, pp 51-67.

4 - Conceição EZE, Lúcio Mª MJR, Rosa SP, Custódio ALV, Andrade RL, Meira. Evaluation of comfort level in desks equipped with two personalized ventilation systems in slightly warm environments. Building and Environment, Volume 45, Issue 3, March 2010, pp. 601-609.

5 - Conceição EZE, Lúcio MªMJR. Evaluation of Thermal Comfort Conditions in a Localized Radiant System Placed in Front and Behind two Students Seated Nearby Warmed Curtains. Building and Environment, Volume 45, Issue 10, October 2010, pp. 2100-2110.

6 - Conceição EZE, Lúcio MªMJR. Evaluation of Thermal Comfort Conditions in a Classroom Equipped With Cooling Radiant Systems and Subjected to Uniform Convective Environment. Applied Mathematical Modelling, Issue 3, Volume 35, March 2011, pp. 1292–1305.

7 - Conceição EZE, Rosa SP, Custódio ALV, Andrade RL, Meira Mª JPA, Lúcio MªMJR. Study of Airflow Around Occupants Seated in Desks Equipped With Upper and Lower Air Terminal Devices for Slightly Warm Environments. International Journal on Heating Air Conditioning and Refrigerating Research. ASHRAE, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., EUA, Volume 16, Number 4, July 2010.

8- Schetelig T, Rabenstein R. Simulation of three-dimensional propagation with multidimensional wave digital filters. IEEE Int. Conf. on Acoustics, Speech & Signal Processing (ICASSP), Seattle, USA, May 1998.

9 - Savioja L, Huopaniemi J, Lokki T, Vaananen R. Creating Interactive Virtual Acoustic Environments. Audio Engineering Society, Inc. 1999; Vol. 47, No.9, 1999 September.

10 - Funkhouser T, Tsingos N, Jot J. Survey of methods for modeling sound propagation in interactive virtual environment systems. 2003.

11 - Funkhouser T, Min P, Carlbom I. Real-time acoustic modeling for distributed virtual environments. Proceedings of the 26th annual conference on Computer graphics and interactive techniques, July 1999; p. 365-374.

12 - Taylor MT, Chandak A, Antani L, Manocha D. RESound: Interactive Sound Rendering for Dynamic Virtual Environments. MM'09, October 19–24, 2009, Beijing, China.

13 - Funkhouser T, Carlbom I, Elko G, Pingali G, Sondhi M, West J. A Beam Tracing Approach to Acoustic Modeling for Interactive Virtual Environments. Computer Graphics (SIGGRAPH `98), Orlando, FL, July 1998, p. 21-32.

14 - ISO 7730. Ergonomics of the thermal environment – Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria. International Standard Organization, Geneva, Switzerland, 2005.

15 - Decreto-Lei nº 96 (2008). Regulamento dos Requisitos Acústicos dos Edifícios. Diário da República, 1.ª Série — N.º110, June 9th. (in Portuguese).