

DOMUS 2.0: A WHOLE-BUILDING HYGROTHERMAL SIMULATION PROGRAM

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ABSTRACT

Recent advances in mathematical models, computer processors and OOP compilers have been motivating the development of the Domus program for whole-building hygrothermal simulation. The Domus program for simulation of multi-zone buildings has been developed in c++ language under C++ Builder environment, which is a fast and precise easy-to-use compiler. The program is available on the PC platform under Windows 9x and NT operating systems. The user interface consists of a series of windows in which the user can enter the relevant input data and review the results. The user can move between other applications when the Domus simulations are running and several Domus projects can be open and running at the same time due to the independence of the graphical interface and the thermal simulation engine. Domus projects with all their input information and results may be saved and reopened. The Domus former version allows the calculation of building thermal and energy performance, neglecting moisture effects. In this Domus version, the interface has been considerably improved so that simulations can be performed in a very-easy way. Additionally, the Umidus program features have been inserted into the Domus code, allowing it to take moisture effects into account. In Conclusion, Domus interface is presented and a hygrothermal simulation of a 3storey building in discussed.

INTRODUCTION

We describe the Domus software for simulation of multizone buildings and analysis of both thermal comfort and energy use. The software Domus has been developed to model coupled heat and moisture transfer in buildings when subjected to any kind of climate conditions, i.e., considering both vapor diffusion and capillary migration.

Domus is a object-oriented software which has been developed in c++ under C++ Builder environment which is fast and precise easy-to-use compiler. The program is available on the PC platform under Windows 9x and NT operating systems. The user interface consists of a series of windows in which the

user can enter the relevant input data and review the results. The user can move between other applications when the Domus simulations are running and several Domus projects can be open and running at the same time due to the independence of the graphical interface and the thermal simulation engine. Domus projects with all their input information and results may be saved and reopened.

Domus development consisted of a CACSD environment creation for the analysis of thermal building performance. The program has a simplified CAD interface so that the user can easily edit the building geometry.

Mendes et al. (2001) presented a first Domus version, in which the calculation of conduction heat transfer through multi-layer walls was done by using the finite-difference approach and, for each zone, it was employed a capacitive lumped model to calculate the temperature and relative humidity. In that version, the moisture effects were not taken into account.

In order to consider the presence of moisture, the capabilities of the heat and moisture transfer program UMIDUS (Mendes et al., 1999) were inserted into the Domus code, allowing then performing whole-building hygrothermal simulations.

Therefore, Domus models predict temperature and moisture content profiles within multi-layer walls for any time step and temperature and relative humidity for each zone. Input files containing hourly data provide information on the conditions at the interior and exterior of a building; a library of material properties is also available. The external convection heat transfer coefficients can be entered as constant values or as functions of temperature difference, wind velocity and direction data.

Domus has been conceived to be a very user- friendly software so that to stimulating a larger number of users in Brazil to use building simulation software and meet Brazilian energy conservation program goals. Besides this aspect, as the weather in Brazil permits the usage of passive architecture, Domus will have a module, which will allow the user to simulate,

in an easy way, passive or low-energy strategies to reach thermal comfort conditions.

In the article, we present the Domus mathematical models and interface. Some illustrative simulation results are also presented.

MATHEMATICAL MODEL

The present building simulation program uses a dynamic model for the analysis of a whole- building hygrothermal behavior. Therefore, a lumped formulation for temperature as well as for water vapor is adopted in each building zone. Eq. 1 describes the energy balance, for a zone submitted to loads of conduction, convection, short-wave solar radiation, inter-surface long-wave radiation, infiltration, ventilation and HVAC system related loads.

$$\dot{E}_t + \dot{E}_g = \rho_{air} c_{air} V_{air} \frac{dT_{int}}{dt} \quad (1)$$

where:

\dot{E}_t energy flow that crosses the room (W)

\dot{E}_g internal energy generation rate (W)

ρ_{air} air density (kg/m³)

c_{air} specific heat of air (J/kg-K)

V_{air} room volume (m³)

T_{int} room air temperature (°C)

The term \dot{E}_t , on the energy conservation equation, includes loads associated to the building envelope (sensible and latent conduction heat transfer), furniture (sensible and latent), fenestration (conduction and solar radiation), openings (ventilation and infiltration) and HVAC systems.

The total conduction heat flux that crosses the control surface of each zone is described below.

Building envelope

The heat released by the building envelope internal porous surfaces is calculated as

$$Q_{wall,S}(t) = \sum_{i=1}^m h_{c,i} A_i [T_{i,x=L}(t) - T_{int}(t)] \quad (2a)$$

for the sensible conduction load and as

$$Q_{wall,L}(t) = \sum_{i=1}^m L(T_{i,x=L}(t)) h_{m,i} A_i [\rho_{v,n,i}(t) - \rho_{v,int}(t)] \quad (2b)$$

for the latent load.

In Eqs. 2a and 2b where A_i represents the area of the i -th surface, h the convection coefficients for (h_c) and mass (h_m), $T_{n,i}(t)$ the temperature at the i -th internal surface of the considered zone, L the vaporization latent heat e ρ_v the water vapor densities. The temperature and vapor density are calculated by the combined heat and moisture transfer model based on the Philip and DeVries (1957) theory (Mendes et al. 2002)

The vapor concentration difference, $\Delta\rho_v$, in Eq. 2b, is normally determined by using the values of previous iterations for temperature and moisture content, generating additional instability. Due to the numerical instability created by this source term, the solution of the linear set of discretized equations normally requires the use of very small time steps, which can be exceedingly time consuming, especially in long-term whole-building hygrothermal simulations.

In order to rise the simulation time step, Mendes et al. (2002) presented a mathematical procedure to calculate the vapor flow, independently of previous values of temperature and moisture content. In this way, the term ($\Delta\rho_v$) was linearized as a linear combination of temperature and moisture content, viz.,

$$\begin{aligned} (\rho_{v,\infty} - \rho_v(s)) &= M_1 (T_\infty - T(s)) + \\ &M_2 (\theta_\infty - \theta(s)) + M_3 \end{aligned} \quad (3)$$

where

$$M_1 = A \frac{M}{\Re} \phi ,$$

$$M_2 = \frac{M}{\Re} \left(\frac{P_s(s)}{T(s)} \right)^{prev} \left(\frac{\partial \phi}{\partial \theta(s)} \right)^{prev} ,$$

$$M_3 = \frac{M}{\Re} \left[\left(\frac{P_s(s)}{T(s)} \right)^{prev} R(\theta^{prev}(s)) + \left[\phi_\infty (R(T_\infty) - R(T^{prev}(s))) \right] \right]$$

In the equations above, the index (s) represents the surface on contact with air and (∞) the air far from that surface.

In order to increase the convergence rapidness, it is interesting to write the volumetric moisture content difference as a humidity ratio difference, which starts from:

$$\theta = \frac{\rho_0}{\rho_l} \frac{1}{\theta_{ar}} \frac{1}{\rho_{ar}} w$$

where, ρ_0 , ρ_l and ρ_{ar} represent densities of the dry-basis material, water and dry-air. The volumetric moisture content, θ_{ar} , can be written as:

$$\theta_{ar} = \eta - \theta_l$$

where η is the porosity and θ_l the liquid phase volumetric moisture content. As the condensable volume (vapor phase volume) is much lower than the liquid phase volume, we can say that:

$$\theta_l = \theta.$$

In this way, we can rewrite the above equation as:

$$\theta = \frac{\rho_0}{\rho_l} \frac{1}{\eta - \theta} \frac{1}{\rho_{ar}} w.$$

Neglecting the dry air density variation with temperature and humidity, the moisture content difference can be given by

$$(\theta_\infty - \theta(s)) = \frac{\rho_0}{\rho_l} \frac{1}{\rho_{ar}} \left(\frac{w_\infty}{\eta - \theta_\infty} - \frac{w(s)}{\eta - \theta(s)} \right).$$

Considering a saturation degree below 20%, it is reasonable to write a mean moisture content as:

$$\bar{\theta} = \frac{(\theta_\infty^{prev} + \theta^{prev}(s))}{2},$$

which gives the following expression:

$$(\theta_\infty - \theta(s)) = \frac{\rho_0}{\rho_l} \frac{1}{\rho_{ar}} \frac{1}{\eta - \bar{\theta}} (w_\infty - w(s))$$

In this way, the vapor concentration difference can now be written as:

$$\left(\rho_{v,i,x=L} - \rho_{v,int} \right) = M_1 (T_{i,x=L} - T_{int}) + M_2' (w_{i,x=L} - w_{int}) - M_3,$$

Therefore, the sensible and latent conduction heat transfer can now be written in terms of temperature

$$Q_{wallL}(t) = \sum_{i=1}^m L(T_{i,x=L}(t)) h_{m,i} A_i \left[M_1 (T_{i,x=L} - T_{int}) + M_2' (w_{i,x=L} - w_{int}) - M_3 \right]$$

and humidity ratio differences.

On the other hand, we can also computing in a similar way the vapor flow that comes from the internal porous surfaces.

It is remarkable the strong coupling between the governing equations. In this way, the use of an algorithm capable to solve simultaneously all equations sets is undeniably useful. Mendes and Philippi (2003) presented the computational performance of the MTDMA (MultiTriDiagonal Matrix Algorithm), applied to the case of strongly-coupled heat and moisture transfer in porous building materials.

A fact that used to motivate engineers and researchers to numerically decouple the governing equations was probably based on the difference between the time scales for both heat and moisture transfer. Nonetheless, besides the mathematical coupling between the terms of conservation equations, the transport coefficients have a strong non-linear dependence on moisture content and temperature. In fact: i) for low moisture content, mass transfer is predominantly in the vapor phase; ii) right after the liquid water has become a continuous phase, small changes in capillary potential may produce high variation in moisture content and liquid transfer by capillarity will be greatly enhanced. This microscopic information of "liquid bridges" that speed up the moisture transport are embedded in the coefficient $D_{\theta L}$; iii) when the moisture content is high, it is likely to occur high evaporation rates at the boundaries, promoting high gradients of moisture content and temperature and making the transport coefficients to change considerably through the physical domain of the porous structure; iv) for the material chosen in this study (lime mortar), moisture

transport coefficients may rapidly change their magnitude by a factor of 100 or even more; v) thermal conductivity may also have a substantial variation at the order of 20%.

All that leads to numerical divergence problems when the physical problem is mathematically decoupled.

For this combined heat and moisture transfer problem through a porous medium, Mendes et al. (2002) discretized the conservation equations by using the control-volume formulation method with a central difference scheme and linearized vapor concentration difference at the boundaries in terms of temperature and moisture content.

The use of MTDMA to solve the discretized set of those governing equations represents an important step to improve calculation methods, because the source term may become smaller and the main diagonal stronger, making the solver much more robust in building simulations where strongly coupled phenomena are present.

Water vapor mass balance

In terms of water vapor balance, it was considered different contributions: ventilation, infiltration, internal generation, porous walls, furniture, HVAC system and people breath. In this way, the lumped formulation becomes:

$$(\dot{m}_{inf} + \dot{m}_{vent})(W_{ext} - W_{int}) + J_b + J_{ger} + J_{porous\ surface} + J_{HVAC} = \rho_{air} V_{air} \frac{dW_{int}}{dt}$$

where:

\dot{m}_{inf} air mass flow by infiltration (kg/s)

\dot{m}_{vent} air mass flow by ventilation (kg/s)

W_{ext} external humidity ratio (kg water/kg dry air)

W_{int} internal humidity ratio (kg water/kg dry air)

J_b water vapor flow from the breath of occupants (kg/s)

J_{ger} internal water-vapor generation rate (kg/s)

$J_{porous\ surfaces}$ water vapor flow from porous

surfaces (walls, partitions and furniture) (kg/s)

J_{HVAC} vapor flow from HVAC systems (kg/s)

ρ_{air} air density (kg dry air/s)

V_{air} room volume (m³)

The water-vapor mass flow from the people breath is calculated as shown in ASHRAE (1993), which takes into account the room air temperature, humidity ratio and physical activity as well.

Boundary Conditions

The external and internal boundary conditions consider long- and short-wave radiations and convection. The Domus hourly weather files provide dry bulb temperature, relative humidity, direct and diffuse solar radiation and wind speed and direction.

Presently, the program reads just weather files in the Domus format (*.dom). In the near future, it will be added options for several weather file formats such as TRY (Test Reference Year), TMY (Typical Meteorological Year) and WYEC (Weather Year for Energy Calculations).

The internal and external convection heat transfer coefficients are also configured on a weather window. In the case, the user wants the coefficients to be calculated in time of execution, just has to click in the option. Domus has correlations for those coefficients obtained by Allandari and Hammond (Clarke, 1985).

For the floor, we can either consider the Dirichlet condition for temperature and moisture content at the lower soil surface or adiabatic and impermeable for deeper surfaces. The ground heat transfer is considered one-dimensional.

DOMUS INTERFACE

The software interface is modularly divided in different parts and is briefly described in the paragraphs below. Fig. 1 shows the main menu.

Building Description Module

This module is responsible by the definition of the building geometry and dimensions. A building can have several zones and each zone can have several walls and each wall can have several layers and each layer shall be defined by its physical characteristics.

The user can interact with building envelope and openings and after defining the geometry, a text file

will be automatically created so that the user can verify all the inputs.

As a building can have several zones, an important aspect is how to geometrically conceive the inter-zone relationship in order to have a generic code. This inter-zone relationship is described by Mendes et al. (2001). As the software allows the user to freely choose the geometry, all the geometric consistency has to be transferred into the code. The theoretic basis for the solution of these complexities is the computational geometry directly turned to arithmetic and logics operations between 2D flat surfaces. DOMUS has incorporated the polyboolean library (Leonov, 1999) as an extern DLL to accomplish these kind of operations. This library is numerically robust and fast, unlike the most polygon clipping libraries on Web.

Only a part of each wall has an adjacency to another zone. The program executes an intersection operation (operation "AND") between both walls. The results will be a region defined for a rectangle. If openings are added within the adjacency area, they should be considered in the intersection operation as well, which increases the computational effort.

The Domus edition interface is very simple, allowing the user to build a construction without much of specific knowledge. For the 3-D visualization panel, it is provided tools to rotate, translate and change building scale and colors. Domus makes use of the OpenGL API to render both 2-D and 3-D graphics applications. Nowadays OpenGL is the premier environment for developing portable, interactive 2-D and 3-D graphics applications. If hardware acceleration is detected, then high quality graphics can be affordable.

Domus uses the *triangle* software (Shewchuk, 1996) that generates a finite-element mesh on walls and ground in order to precisely calculate shape factors and shaded/sunny areas. Triangle is fast, memory-efficient, and robust; it computes Delaunay triangulations and constrained Delaunay triangulations exactly. Guaranteed-quality meshes (having no small angles) are generated using Ruppert's Delaunay refinement algorithm (See triangulation on Fig.-1 bottom right side).

The wall layers are edited in a particular window, where all the available materials, geographical orientation (wall azimuth and inclination), soil properties, painting and other parameters are shown. It provides also some wall samples which are largely employed in Brazil (see Fig. 2).



Figure 2: Module of Brazilian sample walls.

Weather

The external building climate is chosen in a weather configuration window. To make easier, the program load all the existing weather files in a specified folder and list all of them.

The Domus hourly weather files provide dry bulb temperature, relative humidity, direct and diffuse solar radiation and wind speed and direction.

The program also provides a weather summary window and a psychrometrics chart where temperature and relative humidity data presented in the weather file can also be plotted (Fig.3).

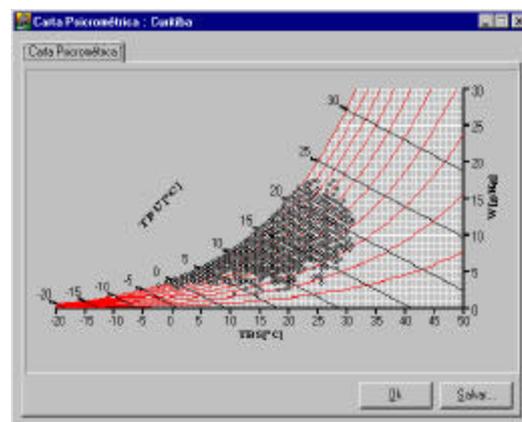


Figure 3 – Weather data information (Temperature and relative humidity) on a psychrometrics chart.

Internal Gains

Internal energy gains for each zone can be entered in a special window where the user sets schedules for internal equipment, lighting, vapor generation, people and external equipment (just for the economy evaluation module).

HVAC Systems

In the HVAC window, the user will be able to specify HVAC equipment for each zone. The user will also be able to define a controller for each equipment in each zone. In the present Domus program version, a model for a heater and a window-type air conditioner is available.

Output Reports

Before executing the simulation, the user has to choose all the types of reports that the program will have to generate. The program provides a great variety of report options such as hourly reports for temperature, relative humidity, thermal comfort level (PMV and PPD), temperature and moisture content distributions within any building wall, energy consumption, thermal loads, energy costs, and monthly general statistics.

It is possible to the user to monitor the temperature and/or the controller output with different simulation time steps. It is important to remember that for small time steps, the program will generate large files.

RESULTS

We have chosen as a simulation sample the 3-storey building shown in Fig. 4. In each zone, a 1mx1m window is placed on either North or south façades. We have selected the Curitiba weather data file and a 5-min. time step.

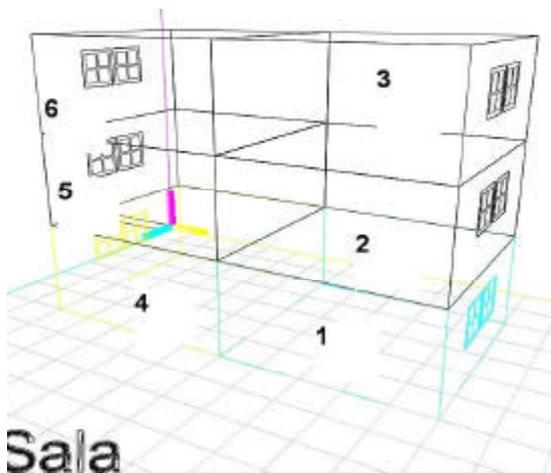


Fig. 4: Illustration generated by the DOMUS 3D building description module of the building under analysis.

Fig. 5 presents the temperature and moisture content profiles within the South-oriented wall of zone number 4 on January 10th. By comparing Figures 5a and 5b, we notice a reduction on the moisture content profile, showing that the wall dries out during daytime. On the other hand, during the nighttime, the

humidity ratio is increased and the wall absorbs a higher amount of moisture, reaching the highest values around 6 am. We also observe, by comparing Figs. 5a and 5c, an expressive difference on the temperature spatial distribution when moisture is ignored, mainly at 6am. In Fig. 5, point 1 and 21 correspond respectively to external and internal surfaces temperature.

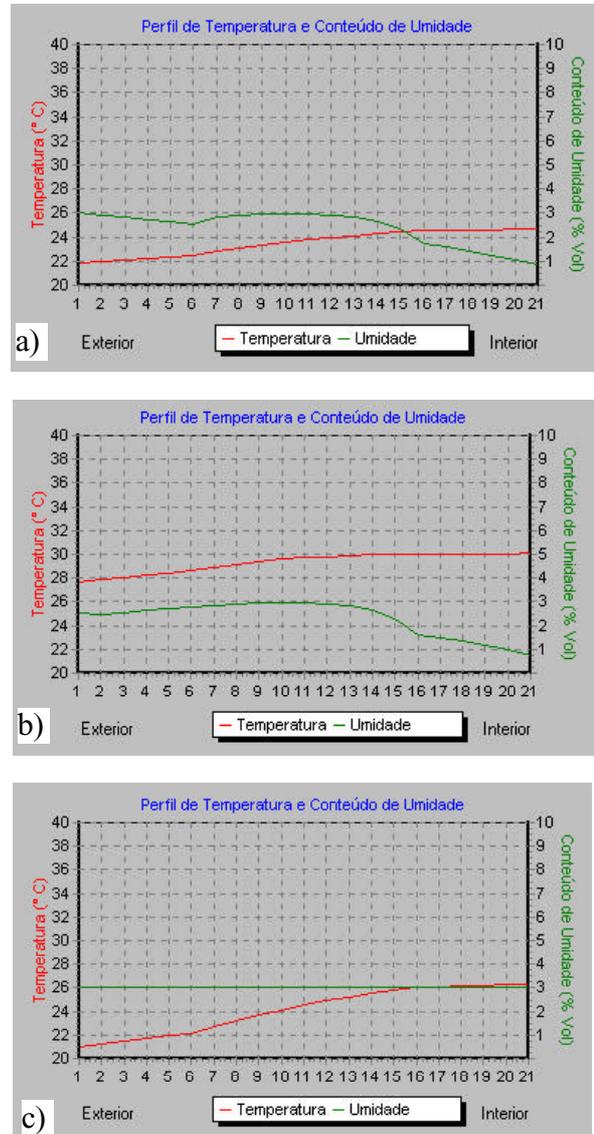


Figure 5: Temperature and moisture content profiles within the South-oriented wall of zone number 4 on January 10th. a) with moisture effects at 6am. b) with moisture effects at 6pm. c) without moisture effects at 6am.

A useful Domus feature is the presence of Fanger's thermal comfort model for PMV and PPD prediction. Figure 6 shows these indices for zone number 1 during the first week of July.

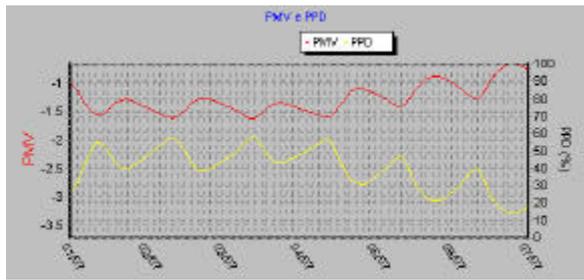


Figure 6: Fanger's indices for zone number 1 in July.

Fig. 7 shows the comfort indices using an on-off heating system, noticing an improvement of the zone thermal comfort. Fig. 8 presents the Temperature and relative humidity evolution using an on-off electric heater.

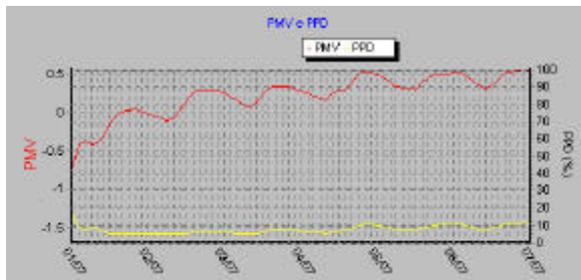


Figure 7: Thermal comfort indices using an on-off electric heater in July.

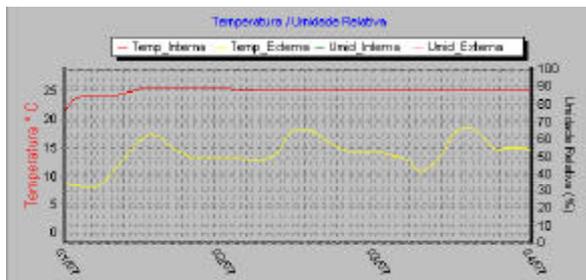


Figure 8: Temperature and relative humidity using an on-off electric heater in July.

CONCLUSIONS

We have described the Domus building simulation program, which was developed for whole-building hydrothermal analysis, by using the finite-volume approach and the mathematical method developed by Mendes et al. (2002). The use of this method avoids numerical oscillations, since it keeps the discrete equations strongly coupled between themselves, preventing the occurrence of physically unrealistic behavior when time step is increased and producing

an unconditionally-stable numerical method, which is very suitable to be used in building yearly energy simulation programs.

The Domus program interface for simulation of multizone buildings has been developed in c++ language under C++ Builder environment using a OpenGL graphical interface which is a fast and precise easy-to-use compiler. The user interface consists basically of a series of windows in which the user can enter the relevant input data and review the results.

Simulations of a 6-zone building was performed, showing that Domus is an easy-to-use tool for a whole-building hydrothermal simulation. Some results showed also the importance of taking moisture into account.

The program provides a great variety of report options such as hourly reports for temperature, relative humidity, thermal comfort level (PMV and PPD), energy consumption, thermal loads, energy costs, and monthly general statistics.

For further work, we intend to incorporate some natural ventilation models.

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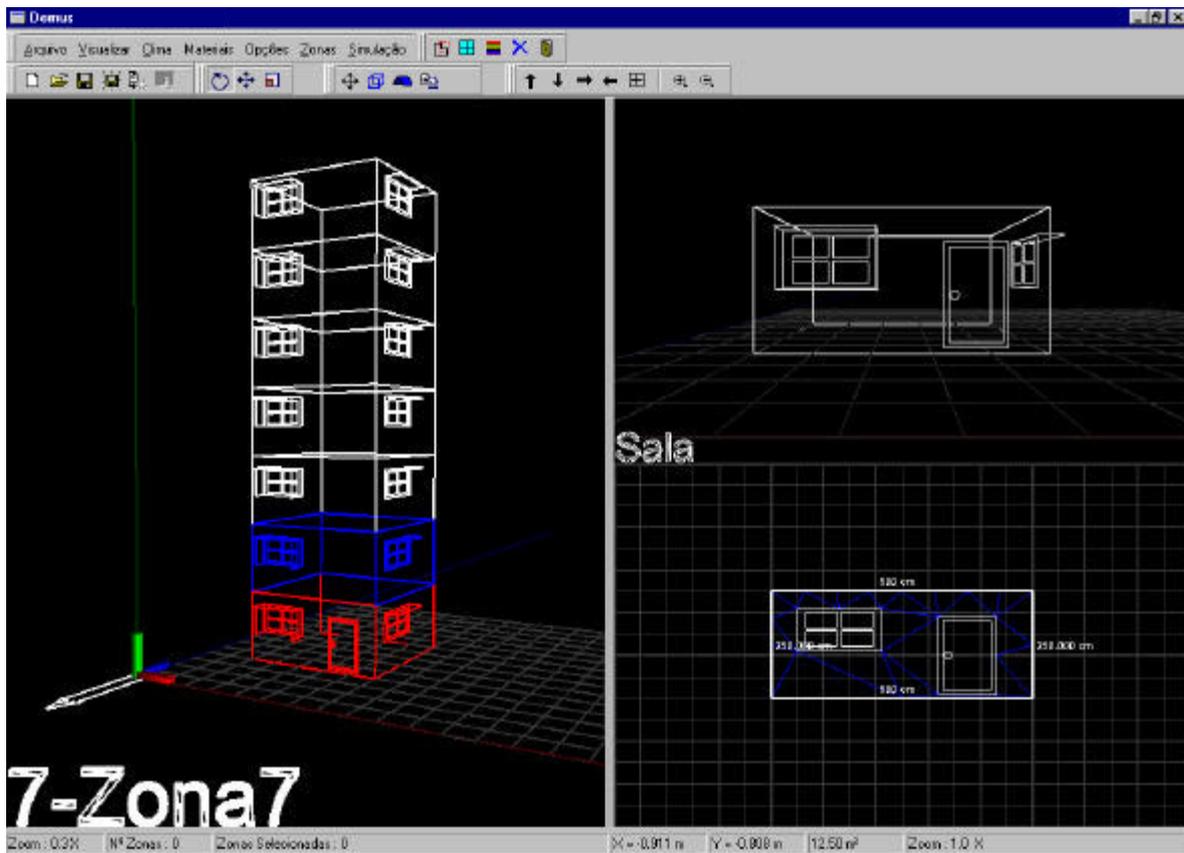


Figure 1: Domus main menu with a 7-storey building.