Thermo-energetic simulation in openmodelica and energyplus: Test case from standard VDI 2078

Simulação termoenergética no openmodelica e no energyplus: Caso de teste da norma VDI 2078

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Marcelo Schramm
PhD in engineering, area of Energy and Transport Phenomena
Institution: Universidade Federal de Pelotas (UFPel)
Address: Pç Domingos Rodrigues, sala A205.6, Centro, Pelotas - RS, CEP: 96010-450
E-mail: schrammmarcelo@gmail.com

Leticia Jenisch Rodrigues
PhD in Engineering in the area of Energy and Transport Phenomena
Institution: Universidade Federal do Rio Grande do Sul (UFRGS)
Address: Rua Sarmento Leite, 452, sala 203, Centro Histórico, Porto Alegre – RS, CEP: 90050-170
E-mail: leticia.jenisch@gmail.com

Diandra Garcia Braatz
Bachelor in Mechanical Engineering
Institution: Universidade Federal do Rio
Address: Karl-Grillenberger-Strasse, 3a, 90402, Nürnberg, Alemanha
E-mail: braatzdiandra@gmail.com

ABSTRACT
In this work, the test case 1 of german standard VDI 2078 is used to compare the softwares OpenModelica and EnergyPlus. The mentioned standard provides calculation methods of thermal load and temperature and test cases for validation of thermal zones' models. This case's behavior was evaluated in both softwares, keeping the reference values provided by the standard. Pearson's correlation coefficient calculated between the values obtained by OpenModelica and EnergyPlus for zone air temperature, operative temperature and thermal load for the thermal zone type M are, respectively, 0,98 (very strong correlation), 0,87 (strong correlation) and 0,99 (very strong correlation). Among the reasons for deviations in results from both programs are the calculation method of thermal resistances and capacitances and of radiative coefficient, as well as the treatment of zone's internal mass.

Keywords: OpenModelica, EnergyPlus, thermal load, operative temperature, VDI 2078.

RESUMO
Neste trabalho, o caso de teste 1 da norma alemã VDI 2078 é usado para comparar os softwares OpenModelica e EnergyPlus. A norma mencionada fornece métodos de cálculo de carga térmica e temperatura e casos de teste para validação de modelos de zonas

térmicas. O comportamento desse caso foi avaliado em ambos os softwares, mantendo os valores de referência fornecidos pela norma. Os coeficientes de correlação de Pearson calculados entre os valores obtidos pelo OpenModelica e pelo EnergyPlus para a temperatura do ar da zona, a temperatura operativa e a carga térmica para a zona térmica tipo M são, respectivamente, 0,98 (correlação muito forte), 0,87 (correlação forte) e 0,99 (correlação muito forte). Entre as razões para os desvios nos resultados de ambos os programas estão o método de cálculo das resistências e capacitâncias térmicas e do coeficiente radiativo, bem como o tratamento da massa interna da zona.

Palavras-chave: OpenModelica, EnergyPlus, carga térmica, temperatura operacional, VDI 2078.

1 INTRODUCTION

Brazil is among the ten countries which most use air conditioning equipment in the world (TOCCHIO, 2020), given its climatic characteristics. In addition, if there are no actions against climate changes, global warming will cause the use of air conditioning to double in the next decade (BEZERRA et al., 2021). This bigger energy consumption for cooling means an increase in the carbon emissions, which brings as effect more heat. Cohen et al. (2020) describe the unprecedented increase in global cooling demand as a blind spot in the sustainability debate.

The concept of energy efficiency in buildings is related to the needed energy supply in order to achieve desirable thermal conditions, which reduce the energy consumption. The design of appropriate heating and cooling systems is one of the best ways to lower the energy costs in buildings (OMER et al., 2008). Therefore, the energetic modeling and simulation are important tasks, since they allow detailed investigation of interactions inside the system and optimization of the acclimatization project.

The VDI (*Verein Deutscher Ingenieure*, in English German Engineers Association) provides standards, as: VDI 6020, Requirements to be met by calculation methods for the simulation of thermal-energy efficiency of buildings and building installations; VDI 6007, Calculation of transient thermal response of rooms and buildings; and VDI 2078, Calculation of thermal loads and room temperatures (design cooling load and annual simulation). The latter served as base for the present article. The thermal models must be tested in order to minimize errors and attest the quality of the results. Thus, several test cases are provided by the standard to validate the models.

Hua et al. (2016) applied the IBPSBuilding package, which is a thermal simulation tool in Modelica (MODELICA, 2022) language, in test cases of VDI 6007-1 standard.

Thereby, they compared results of internal temperature, operative temperature and thermal load (cooling and heating) with the reference provided by the standard. Initial values, transient response and consistency in steady state could be examined. The article concludes that, in order to reduce the deviations encountered in the thermal load calculation, there should be an increase in the number of RC circuits (resistor-capacitor) representing each building's layer.

Fuchs et al. (2014) compared the results of twelve test cases of building models proposed by the VDI 6007 and the ISO 13790 standards in Modelica (MODELICA, 2022) language. The goal was to analyze if the model proposed by the standard would be suitable to the application in district networks. The conclusion was positive in this sense, leaving as future work measures to introduce stochastic variations (so that occupation and usage profiles would be more realistic) and enabçe more efficient workflows, with limited parametrization effort.

The Modelica (MODELICA, 2022) language, although very widespread in countries like Germany, is still little used in Brazil. EnergyPlus, in contrast, is a thermo-energetic simulation tool very much accepted in Brazilian territory. Thus, the goal of this article is the verification of the OpenModelica and EnergyPlus softwares, using one test case of the validation section of the VDI 2078 standard, so that the results of the simulations obtained by both models could be compared. The model of building's elements represented by symmetrical and asymmetrical RC circuits used in the works of Hua et al. (2016) and Fuchs et al. (2014) were also used in the present article.

2 THEORETICAL FOUNDATION

In this Section, concepts and definitions used in the course of the work are presented. Fundamental subjects of heat transfer are covered, as well as important information for the execution of thermal simulations.

2.1 WEATHER FILE - TEST REFERENCE YEAR

The weather file of type TRY (Test Reference Year) provides average years with climate data, with a time step of one hour. It describes the climate history of a region based on long-term averages. Therefore, accidental variations of a particular year are not taken into consideration (LAMBERTS and Duarte, 2016).

According to the VDI 6007 standard, for the calculation of the transient response of rooms and buildings, the TRY must contain, at least, the following parameters: external air temperatura, direct solar radiation - corresponding to a horizontal or normal surface - , diffuse sky radiation - corresponding to a horizontal surface -, amount of clouds, atmospheric irradiation - corresponding to a horizontal surface -, and radiant heat emission from the Earth's surface.

2.2 CONVECTIVE HEAT TRANSFER

The convective heat transfer, Q_{conv}, in W, can be written as

$$Q_{conv} = \alpha_{conv} A (T_1 - T_2), \quad (1)$$

in which A is the heat transfer area, in m^2, $(T_1 - T_2)$ is the temperature difference between both mediums, in K, and α_{conv} is the convective coefficient, in W/m^{2}K.

According to Holman (2010), α_{conv} is calculated based on the fluid's properties and its flow on a surface. Thus, for example, for a laminar flow, with constant velocity, on a flat plate, in which the heat flow from the plate to the fluid is kept constant, α_{conv} is given by

$$\alpha_{conv} = Nu \frac{k}{x}, \quad (2)$$

in which k is the thermal conductivity of the fluid, in W/mK, x is the distance until the leading edge of the plate, in m, and Nu is the Nusselt number. This number is calculated from

$$Nu = 0{,}453 Re^{1/2} Pr^{1/3}, \quad (3)$$

in which Re is the Reynolds number, dependent on the flow regime, and Pr is the Prandtl number, given by the ratio between kinematic viscosity and thermal diffusivity.

2.3 RADIANT HEAT TRANSFER

The net radiant heat rate, Q_{rad}, in W, between a surface and its surroundings is

$$Q_{rad} = \varepsilon \sigma A (T_1^4 - T_2^4), \quad (4)$$

in which $\boldsymbol{\varepsilon}$ is the surface's emissivity, $\boldsymbol{\sigma}$ is the Stefan-Boltzmann constant ($\boldsymbol{\sigma}$ = 5,67 10^{-8} W/m^2K^4), $\boldsymbol{T_1}$ is the surface temperature, in K, and $\boldsymbol{T_2}$ is the surrounding temperature, in K. In order to linearize Equation (4), the radiant heat transfer coefficient is introduced,

$$\boldsymbol{\alpha_{rad}} = \boldsymbol{\varepsilon\sigma}(\boldsymbol{T_1} + \boldsymbol{T_2})(\boldsymbol{T_1^2} + \boldsymbol{T_2^2}). \qquad (5)$$

Thus, the radiant heat transfer can be written as

$$Q_{rad} = \alpha_{rad}A(T_1 - T_2). \qquad (6)$$

2.4 EQUIVALENT OUTDOOR TEMPERATURE

For the consideration of solar radiation on the external walls of a thermal zone, the VDI 6007 standard adds correction terms to the outdoor air temperature, resulting in the equivalent outdoor temperature. This temperature can be calculated by

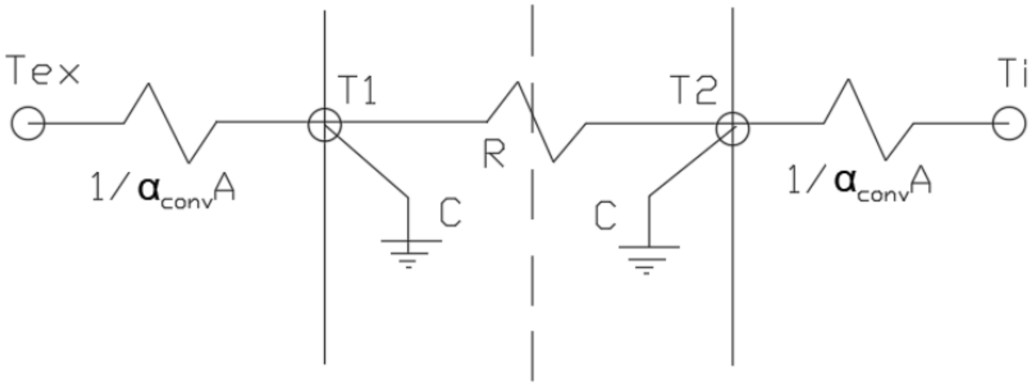
$$T_{ex,eq} = T_{ex} + \Delta T_{ex,eq,ol} + \Delta T_{ex,eq,oc}\ , \qquad (7)$$

in which $\boldsymbol{T_{ex}}$ is the outdoor air temperature, in K, $\boldsymbol{\Delta T_{ex,eq,ol}}$ is the difference in equivalent outdoor temperature owing to long-wave radiation exchange, in K, and $\boldsymbol{\Delta T_{ex,eq,oc}}$ is the difference in equivalent outdoor temperature owing to short-wave radiation exchange, in K. Both correction temperatures, $\boldsymbol{\Delta T_{ex,eq,ol}}$ and $\boldsymbol{\Delta T_{ex,eq,oc}}$, depend on the radiant heat transfer coefficient, $\boldsymbol{\alpha_{rad}}$.

2.5 EQUIVALENT CIRCUIT FOR WALL MODELING

In the present article, the equivalent circuit model is considered for the representation of heat transfer through walls. Seem (1987) described the unidimensional heat transfer through a flat homogeneous wall, with constant thermal properties, as a finite-difference model with two nodes, illustrated in Figure 1. The model considers a one-layer wall and convective heat transfer on both sides.

Figure 1 - Finite-difference model with two nodes of a flat wall. Source: Adapted from Seem (1987).



Thus, the energy balance at both nodes results in the following differential equations

$$C\frac{dT_1}{dt} = \alpha_{conv}A(T_{ex} - T_1) + \frac{A(T_2 - T_1)}{R}, \quad (8)$$
$$C\frac{dT_2}{dt} = \alpha_{conv}A(T_i - T_2) + \frac{A(T_1 - T_2)}{R}, \quad (9)$$

in which C is the thermal capacitance, in J/K, $\boldsymbol{T_1}$ is the temperature of node 1, in K, $\boldsymbol{T_2}$ is the temperature of node 2, in K, $\boldsymbol{T_{ex}}$ is the outdoor air temperature , in K, $\boldsymbol{T_i}$ is the internal air temperature, in K, and $\boldsymbol{R}$ is the thermal conduction resistance, in K/W. The thermal conduction resistance can be calculated by

$$R = \frac{L}{k}, \quad (10)$$

in which L is the wall's thickness, in m, and k is the thermal conductivity of the wall, in W/mK. The thermal capacitance of each node can be calculated by

$$C = \frac{\rho c L}{2}, \quad (11)$$

in which $\boldsymbol{\rho}$ is the specific mass of the wall's material, in kg/m^3 and c is the specific heat of the wall's material, in J/kgK.

The heat flow on the internal side of the wall can be calculated by

$$Q_i'' = \alpha_{conv}(T_i - T_2). \quad (12)$$

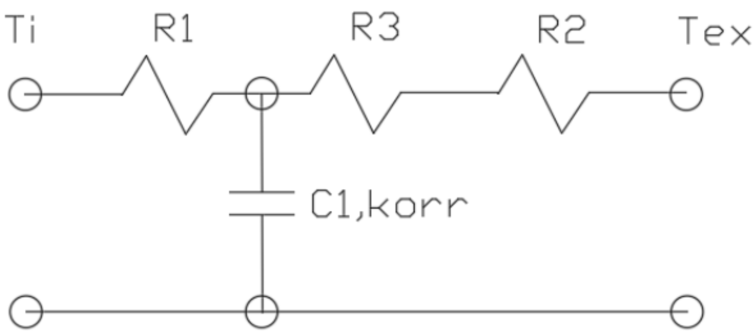
The heat flor on the external side of the wall can be calculated by

$$Q''_{ex} = \alpha_{conv}(T_1 - T_{ex}). \quad (13)$$

EnergyPlus uses the matrix format of Equations (8) until (13) in its calculation base, with input data being the environmental temperatures and the output data being the heat flow.

The VDI 6007 standard, on the other hand, models the external walls as asymmetrical thermally charged components, represented by three resistances and one capacitor, as illustrated by Figure 2. The TEASER tool, better explained in Subsection 4.1, used this format for the calculation of heat conduction through external walls, and the convection calculation is done separately, following Equation (1).

Figure 2 - Equivalent RC circuit model, proposed by VDI 6007 standard. Source: Adapted from VDI 6007 (2015).



The R_1, R_2, and R_3 resistances are defined as

$$\boldsymbol{R_1} = \frac{1}{A}\frac{(Re\_a_{22}-1)Re\_a_{12}+Im\_a_{22}\,Im\_a_{12}}{(Re\_a_{22}-1)^2+Im\_a_{22}{}^2}, \quad (14)$$

$$\boldsymbol{R_2} = \frac{1}{A}\frac{(Re\_a_{11}-1)Re\_a_{12}+Im\_a_{11}\,Im\_a_{12}}{(Re\_a_{11}-1)^2+Im\_a_{11}{}^2}, \quad (15$$

$$\boldsymbol{R_3} = \left(\frac{1}{A}\sum_{v=1}^{n} \frac{L_v}{k_v}\right) - \boldsymbol{R_1} - \boldsymbol{R_2}, \quad (16)$$

in which Re_a_{ij} e Im_a_{ij} are the real and imaginary parts, respectively, which are written as

$$Re\_a_{11} = Re\_a_{22} = cosh\sqrt{\frac{1}{2}\omega_{BT}RC}\, cos\sqrt{\frac{1}{2}\omega_{BT}RC}, \quad (17)$$

$$Im\_a_{11} = Im\_a_{22} = sinh\sqrt{\frac{1}{2}\omega_{BT}RC}\, sin\sqrt{\frac{1}{2}\omega_{BT}RC}, \quad (18)$$

$$Re\_a_{12} = R\sqrt{\frac{1}{2\omega_{BT}RC}}\,(cosh\sqrt{\frac{1}{2}\omega_{BT}RC}\,sin\sqrt{\frac{1}{2}\omega_{BT}RC}$$

$$+sinh\sqrt{\frac{1}{2}\omega_{BT}RC}\,cos\sqrt{\frac{1}{2}\omega_{BT}RC}), \quad (19)$$

$$Im\_a_{12} = R\sqrt{\frac{1}{2\omega_{BT}RC}}\,(cosh\sqrt{\frac{1}{2}\omega_{BT}RC}\,sin\sqrt{\frac{1}{2}\omega_{BT}RC}$$

$$-sinh\sqrt{\frac{1}{2}\omega_{BT}RC}\,cos\sqrt{\frac{1}{2}\omega_{BT}RC}), \quad (20)$$

$$Re\_a_{21} = \frac{-1}{R}\sqrt{\frac{1}{2}\omega_{BT}RC}\,(cosh\sqrt{\frac{1}{2}\omega_{BT}RC}\,sin\sqrt{\frac{1}{2}\omega_{BT}RC}$$

$$-sinh\sqrt{\frac{1}{2}\omega_{BT}RC}\,cos\sqrt{\frac{1}{2}\omega_{BT}RC}), \quad (21)$$

$$Im\_a_{21} = \frac{1}{R}\sqrt{\frac{1}{2}\omega_{BT}RC}\,(cosh\sqrt{\frac{1}{2}\omega_{BT}RC}\,sin\sqrt{\frac{1}{2}\omega_{BT}RC}$$

$$-sinh\sqrt{\frac{1}{2}\omega_{BT}RC}\,cos\sqrt{\frac{1}{2}\omega_{BT}RC}), \quad (22)$$

in which $\boldsymbol{\omega_{BT}}$ is the angular frequency, in s^{-1}.

The $C_{1;korr}$ capacitance is defined as

$$C_{1;korr} = A\frac{1}{\omega_{BT}\,R_1\,A}\frac{R_W\,A-Re\,a_{12}\,Re\,a_{22}-Im\,a_{12}Im\,a_{22}}{Re\,a_{22}\,Im\,a_{12}-Re\,a_{12}Im\,a_{22}}, \quad (23)$$

in which

$$R_W = R_1 + R_2 + R_3. \quad (24)$$

2.6 OPERATIVE TEMPERATURE

Lamberts and Duarte (2016) define that the operative temperature summarizes a body's heat loss which is subjected to a real environment with unequal effects on all sides. Therefore, it is a theoretical temperature which causes a heat loss equivalent to all the phenomena which cause this loss in the case in which the body would be in an imaginary environment subjected to one homogeneous temperature and can be calculated by

$$T_{op} = pT_i + (1-p)\,T_r, \quad (25)$$

in which p is the radiant fraction, estimated based on the air velocity, and $\boldsymbol{T_r}$ is the mean radiant temperature. Equation (25) is used by EnergyPlus.

The operative temperature is defined, on the other hand, by VDI 6007 standard, as the mean of the air temperature inside the analyzed room and the mean radiant temperature of the surfaces that enclose the room. ABRAVA (2003) describes it as the uniform temperature of an imaginary black room, in which a person would exchange the same amount of heat through radiation and convection as in a non-uniform real room. Also, informs that, in air velocities lower than 0,4 m/s, the operative temperature calculation is close to the arithmetic mean of the air temperature and the mean radiant temperature of the room. Since the present article analyzes closed environments, the simplification was considered in OpenModelica, that is,

$$T_{op} = \frac{T_i+T_r}{2}. \quad (26)$$

2.7 OPENMODELICA AND IBPSA LIBRARY

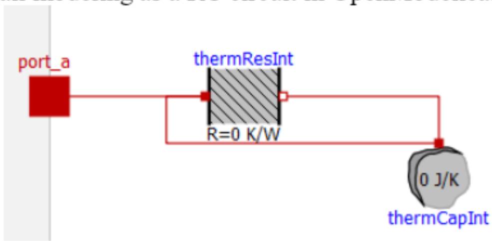
The Modelica (MODELICA, 2022) language is used for the modeling of physical systems. It enables the connection of components governed by mathematical equations and its object orientation allows the reuse of models. One example of code in Modelica (MODELICA, 2022) language to model the convective heat transfer is shown in Figure 3.

Figure 3 - Example of a code fragment in Modelica (MODELICA, 2022) language: convection modeling.
Source: IBPSA, 2022.

```
within Modelica.Thermal.HeatTransfer.Components;
model Convection
  "Lumped thermal element for heat convection (Q_flow = Gc*dT)"
  SI.HeatFlowRate Q_flow "Heat flow rate from solid -> fluid";
  SI.TemperatureDifference dT "= solid.T - fluid.T";
  Modelica.Blocks.Interfaces.RealInput Gc(unit="W/K")
    "Signal representing the convective thermal conductance in [W/K]"
    annotation (Placement(transformation( ...);
  Interfaces.HeatPort_a solid annotation (Placement(transformation(extent={{ ...);
  Interfaces.HeatPort_b fluid annotation (Placement(transformation(extent={{ ...);
equation
  dT = solid.T - fluid.T;
  solid.Q_flow = Q_flow;
  fluid.Q_flow = -Q_flow;
  Q_flow = Gc*dT;
  annotation ( ...);
end Convection;
```

OpenModelica is an open-source environment for the simulation of physical systems. It allows the visualization of models in the form of diagrams, as illustrated by Figure 4. Also, after the code's compilation, it allows plotting the results in graphs.

Figure 4 - Internal wall modeling as a RC circuit in OpenModelica. Source: IBPSA, 2022.



IBPSA (International Building Performance Simulation Association) is an association of researchers, developers and professionals dedicated to improving the design, construction, operation and maintenance of new and existing buildings around the world (IBPSA, 2022). The IBPSA library for Modelica (MODELICA, 2022) language contains basic thermal models for buildings, as the weather file reader, controllers and thermal zone models, as equivalent RC circuits.

3 CASE STUDY AND IMPORTANT CONSIDERATIONS

The case study is the modeling and simulation of one test case from VDI 2078 standard in the softwares OpenModelica and EnergyPlus, for comparison of the obtained results and analysis of the reasons for possible deviations.

3.1 THERMAL ZONE TYPES

VDI 2078 standard defines five thermal zone types, categorized based on their construction characteristics: *XL* (very light), *L* (light), *M* (medium), *S* (heavy), *XS* (very heavy).

The parameters thickness (in m), thermal conductivity (in W/mK), specific mass (in kg/m^3) and specific heat (in J/kgK) are provided for each material of external and internal walls, floor, roof, window and door. Every thermal zone has a window with 5,13 m^2 of area facing south, internal wall and an internal door. The tables which contain the mentioned construction data are provided in Annex I.

3.2 TEST CASE

The analyzed test case is test case 1. The behavior of thermal load and operative temperature of a thermal zone with internal temperature of 295,15 K (22 °C) are requested. The simulation must be done for all thermal zone types, from *XL* to *XS*. Further information concerning test case 1 can be found in Annex 1.

3.3 PARAMETERS AND ADOPTED HYPOTHESIS

This Subsection aims to describe the parameters and hypothesis fixed by VDI 2078 standard, which were used in the modeling of the test case. Also, here simplifications made for the present article are described.

3.3.1 Internal gains hypothesis

The internal gains for the test case considered here consist in heat emitted by three categories: Persons, lighting and others. The category "others" was inserted in the simulations as machines. The hypothesis used for each category are defined below:

Persons: The people inside the zone execute seated activities, which means activity level II, in which 125 W/person are emitted. The dry heat emission can be assumed with sufficient accuracy to consist of equal amounts of radiant and convective heat emissions.

Lighting and machines: The maximum lighting power is 240 W and for machines it is 300 W. The dry heat emission can be assumed with sufficient accuracy to consist of equal amounts of radiant and convective heat emissions.

The analyzed thermal zones have working occupation, which could be office, school or laboratory, for example. Seven working days per week were considered. The tables containing information on internal gains are provided in Annex II.

3.3.2 Heat transfer coefficients

The heat transfer coefficients are divided in: radiant, convective, exterior, interior, vertical and horizontal. Thus, Table 1 provides the values used for each coefficient.

Table 1 - Heat transfer coefficient values

Radiant heat (α_{rad}) (W/m^{2}K)	5,0
Convective heat, external (α_a) (W/m^{2}K)	20,0
Convective heat, internal, vertical surface ($\alpha_{i,\ vert}$) (W/m^{2}K)	2,7
Convective heat, internal, horizontal surface ($\alpha_{i,\ hor}$) (W/m^{2}K)	1,7

4 METHODOLOGY

In order to accomplish the aim of the work, the five thermal zone types mentioned in Subsection 3.1 were modeled in EnergyPlus and OpenModelica for the location Hamburg. EnergyPlus requests the construction parameters, calculating the thermal resistances and capacitances according to method detailed in Subsection 2.5, while, for the model created in OpenModelica, thermal parameters must be provided. Therefore, Subsection 4.1 aims to illustrate the process of calculating the thermal parameters, executed in Python language.

4.1 THERMAL PARAMETERS CALCULATION IN PYTHON LANGUAGE

Por the thermal parameters calculation based on construction parameters, the TEASER (*Tool for Energy Analysis and Simulation for Efficient Retrofit*) tool was used, which is implemented in Python language. Thus, construction elements as walls, floor, roof and window are declared and, as result, needed parameters for the OpenModelica modeling are provided. The input and output data are described below:

- Input data: Heat transfer convective and radiant coefficients for roof, door and window (W/m^2K), specific mass (kg/m^3), specific heat (J/kgK), thermal conductivity (kJ/mK) and thickness (m) of each material, solar heat gain coefficient of window's glass, orientation of roof, floor, walls and window (°), area (m^2) and inclination (°) of roof, floor, walls, window and door.
- Output data: Thermal resistance of roof, floor, walls and window (K/W), remaining resistance of external walls (between wall resistance and wall capacitance) (K/W), capacitance of roof, floor and walls (J/K).

For the calculation of thermal resistances and capacitances, the method detailed in Subsection 2.5 is used. The convective and radiant coefficients used are base on Subsection 3.3.2.

4.2 MODELING IN ENERGYPLUS AND OPENMODELICA

For the modeling of the thermal zones in EnergyPlus and OpenModelica, constructive, climatic and thermal aspects had to be considered. This Subsection details the given treatment for each aspect in both programs.

The weather file used in both programs contained information from the TRY file of Hamburg, provided by the VDI 2078 standard, and, for the lacking fields, information from the EPW file of Hamburg was used. For the thermal aspects of the zone, the construction parameters described in Annex I were declared in the "Material" class of EnergyPlus and the resulting parameters from the TEASER tool (Subsection 4.1) were used in OpenModelica through the zone record file. Figure 5 illustrates the thermal zone of type *M*, modeled in SketchUp for usage in EnergyPlus. The ground temperatures of

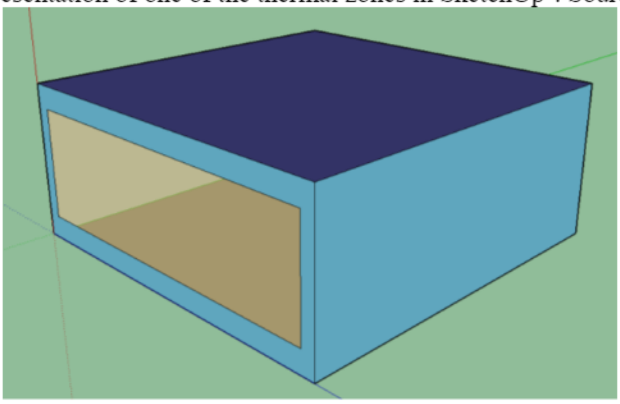
Hamburg for each month of the year were taken from DIN 4710 (2003) standard and used as input data in both programs.

In EnergyPlus, schedules were created in order to represent the zone's occupation and lighting and machine usage, based on information given in Annex II. In OpenModelica, the TXT file with the same information was used as input data for the internal gains calculation.

For the zone's heating and cooling, a PTHP heat pump was declared in EnergyPlus, while, in OpenModelica, a prescribed heat block was used, so that heat could be injected or removed from the zone according to heating or cooling needs. For both cases, temperature set points were provided, where 295,05 K (21,90 °C) was used for heating and 295,25 K (22,10 °C) was used for cooling. The working hours for the heating and cooling equipment are according to reference of VDI 2078 standard.

The convective coefficients mentioned in Subsection 3.3.2 were declared in EnergyPlus in the SurfaceProperty:ConvectionCoefficients class, while, in OpenModelica, they were added to the zone record file. The calculation of the radiant coefficient is done, in EnergyPlus, according to Equation (5), while, in OpenModelica, it is inserted as a given value, according to Subsection 3.3.2.

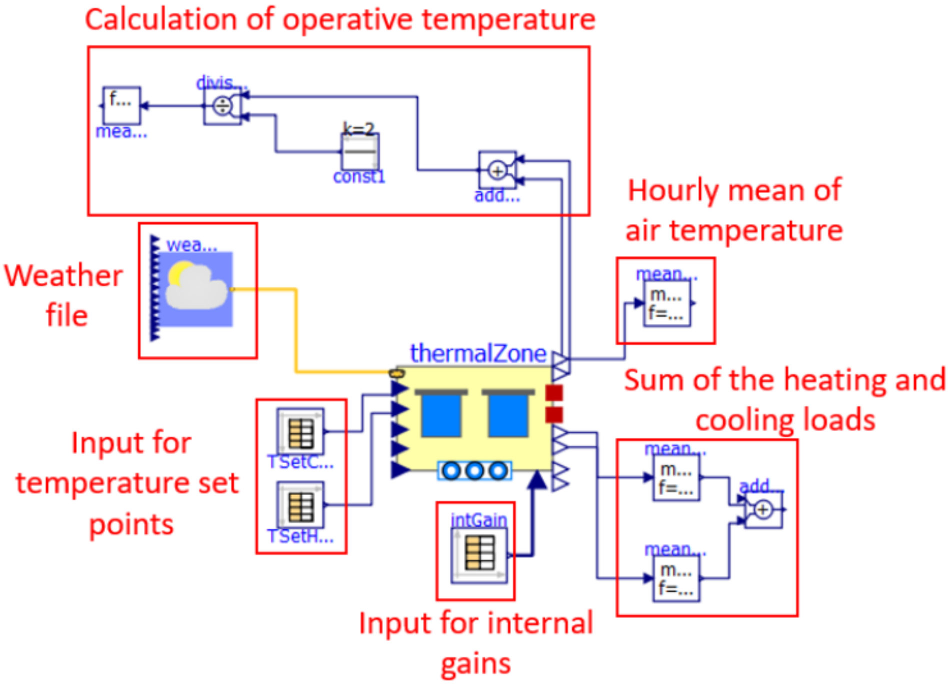
Figure 5 - Representation of one of the thermal zones in SketchUp[1]. Source: The Author.



OpenModelica is a tool which uses blocks for definition of different classes and the connection between them is done through lines, as illustrated by Figure 6. Each block has the needed equations and can own one input portal for the input data and/or one output portal for the output data.

[1] The trial version was used, available for 30 days.

Figure 6 - Model of a thermal zone with input data in OpenModelica. Source: The Author.



5 RESULTS

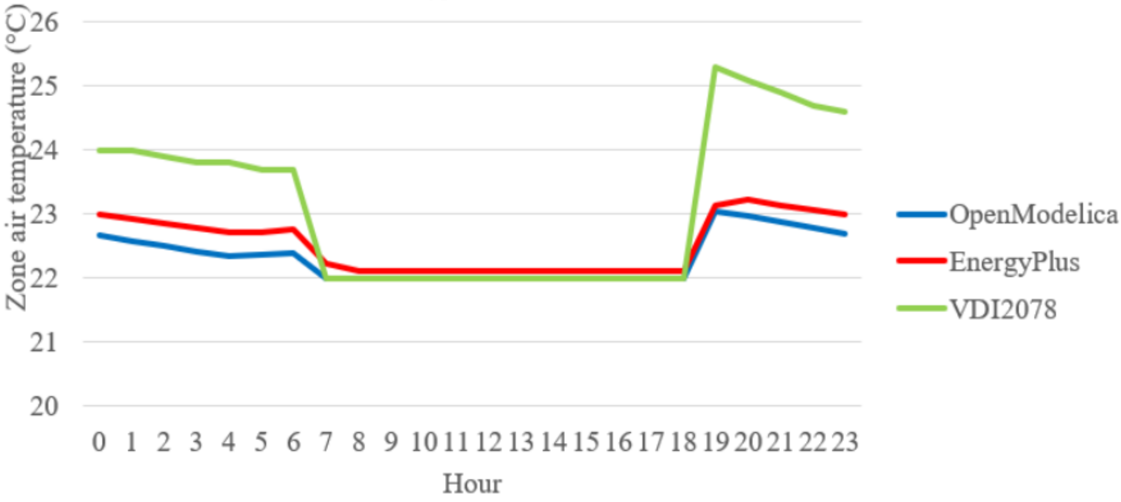
All the five thermal zones mentioned in Subsection 3.1 were simulated, for the 1st of July. Then, results from EnergyPlus and OpenModelica for air temperature, operative temperature and thermal load of thermal zone of type M were analyzed, as well as a comparison with the expected results by VDI 2078 was made. The results for the other types of thermal zones can be found in Appendix A.

5.1 AIR TEMPERATURE COMPARISON - THERMAL ZONE TYPE *M*

Figure 7 illustrates the comparison of air temperature results simulated by EnergyPlus and OpenModelica, as well as the expected values by the VDI 2078 standard. It can be seen that, between 7 a.m. and 6 p.m., the air temperature is 22 °C, since this is the aim value for the heating/cooling equipment of the zone for the occupation period. Also, in EnergyPlus, the zone air is warmer during the night period, which would cause a higher cooling demand during the beginning of the day.

The biggest difference between the values obtained from EnergyPlus and OpenModelica is 0,38 °C at 4 a.m., while the biggest difference between the obtained values from both programs and the standard's values is 2,26 °C at 7 p.m., right after the climatization equipment has been turned off. Pearson's correlation coefficient calculated with the values obtained by OpenModelica and EnergyPlus is 0,98, which, according to Parreira (2018), characterizes a very strong correlation between both curves.

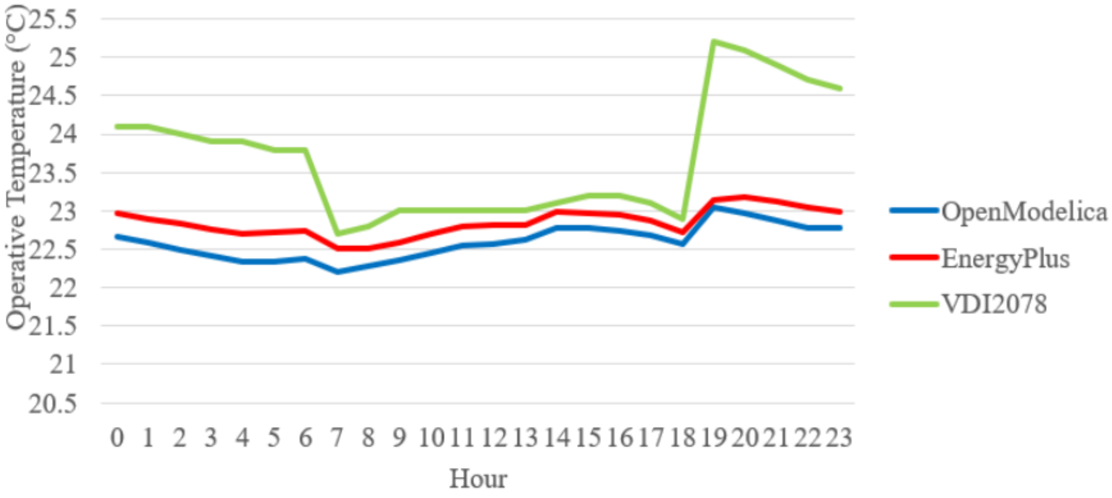
Figure 7 - Air temperature comparison between EnergyPlus, OpenModelica and VDI 2078 for thermal zone type *M*. Source: The Author.



5.2 OPERATIVE TEMPERATURE COMPARISON - THERMAL ZONE TYPE *M*

The operative temperature is differently calculated between OpenModelica and EnergyPlus, as mentioned in Subsection 2.6. Nevertheless, in the course of the day, the values obtained by EnergyPlus are slightly superior to those obtained by OpenModelica (the biggest difference is 0,37 °C at 6 a.m., that is, right before turning on the climatization system). During the period in which the climatization system is turned off, the standard's reference values exceed to a great extent the results from both programs, mainly at the end of the day, the biggest difference being of 2,15 °C. Also, Pearson's correlation coefficient calculated with the values obtained by OpenModelica and EnergyPlus is 0,87, which, according to Parreira (2018), characterizes a strong correlation between both curves.

Figure 8 - Operative temperature comparison between EnergyPlus, OpenModelica and VDI 2078 for thermal zone type *M*. Source: The Author.

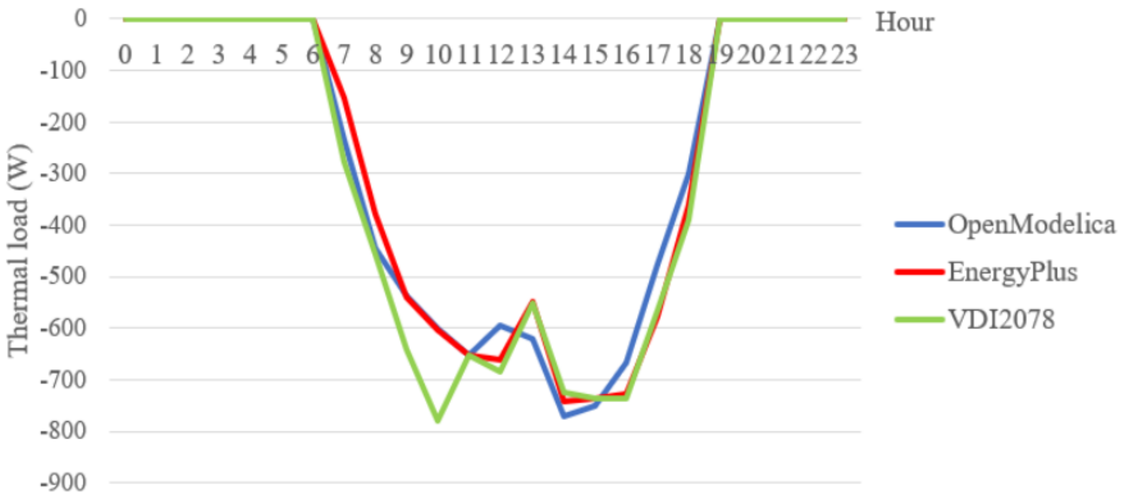


5.3 COOLING LOAD COMPARISON - THERMAL ZONE TYPE *M*

The cooling load is influenced by, among others, the outdoor temperature, insolaton, occupation and zone usage. Thus, it is representative for the analysis of different simulation aspects, such as construction aspects and thermal parameters calculation.

Figure 9 shows similar values for both softwares, however, the behavior in the middle of the day (cooling load reduction) is different for the simulation in OpenModelica in comparison to EnergyPlus and VDI 2078. The biggest difference between both programs is 99,78 W at 5 p.m., and between the programs and the standard is 179,70 W at 10 a.m. Pearson's correlation coefficient calculated with the values obtained by OpenModelica and EnergyPlus is 0,99, which, according to Parreira (2018), characterizes a very strong correlation between both curves.

Figure 9 - Cooling load comparison between EnergyPlus, OpenModelica and VDI 2078 for thermal zone type *M*. Source: The Author.



5.4 REASONS FOR DEVIATIONS BETWEEN ENERGYPLUS, OPEN MODELICAAND VDI 2078

As shown in Subsections 5.1 to 5.3, there are deviations between the simulation results from OpenModelica and EnergyPlus. There is, however, a bigger difference between them and the reference values provided by the VDI 2078 standard. One clear reason for the divergence between simulation results and standard's values is the non-usage of one procedure foreseen by the standard: the Cooling Design Period. It is a stabilization period, in which moments of extreme weather are considered, divided in periods of preliminary calculations, a start-up calculation and Cooling Design Day calculation. The values used for each period should be taken from the DIN 4710 standard. Thus, since, instead of this process, the TRY weather file was used, differences between the simulation results and the standard's values can be expected.

For the deviations encountered between the results obtained by both simulation tools, there are some possible explanations, which are:

- The radiant heat transfer coefficient is an input value in OpenModelica (according to Subsection 3.3.2), used directly in the equivalent outdoor temperature calculation. In EnergyPlus, on the other hand, it is calculated according to Equation (5), that is, using the declared materials' emissivity, the surroundings and surface's temperatures. Therefore, in EnergyPlus, hourly values are calculated for this coefficient, while, in OpenModelica, it is a constant value.

- The thermal resistance of conduction and capacitance calculations are done differently by the TEASER tool and by EnergyPlus, according to what has been mentioned in Subsection 2.5.
- The model created in OpenModelica uses the equivalent outdoor temperature, which depends on the radiant heat transfer coefficient and summarizes the influence of the long and short wave radiation on the thermal zone's external surfaces. This temperature is used in the convective heat transfer calculation between the external surfaces and the environment. In EnergyPlus, however, the convective and radiant heat transfer are separately calculated, according to Equations (1) and (6).
- EnergyPlus, by default, does not consider the internal masses's capacitance. Thus, for the present case, the internal wall and door do not contribute to the thermal inertia of the zone. The model implemented in OpenModelica, on the other hand, considers the capacitance of the internal masses.

6 CONCLUSION

The executed analysis aimed to investigate the differences in the thermo-energetic simulation in programs OpenModelica and EnergyPlus. One validation test case from VDI 2078 was used as base. Operative temperature, zone air temperature and thermal load results could be compared between both softwares and with the reference values provided by the standard.

The mentioned results were similar between the simulation tools, and hipotesis were made for the encountered deviations, according to Subsection 5.4. For the divergences encountered between the programs' values and the ones provided by the standard, the non usage of the Cooling Design Period and Cooling Design Day procedures is a likely explanation. In addition, EnergyPlus is a program which uses the C++ language, implemented specifically for thermo-energetic simulation of buildings, while Modelica (MODELICA, 2022) is a simulation language for different physical systems, which, with the adequate packages, can also execute thermo-energetic simulations.

The present article is unprecedented, since it enables the verification of a test case of VDI 2078 in two established softwares. This represents the fulfillment of an existing demand. As a result, there is the possibility of extension of the executed analysis, as the modeling and simulation of test cases 2 to 16 from VDI 2078.

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ANNEXES

ANNEX I - Constructive parameters of simulated thermal zones

Table 2 - Constructive parameters of thermal zone of type *XL*. Source: Adapted from VDI 2078 (2015).

Construction element	Area (m2)	Layers	Thickness (m)	Conductivity (W/mK)	Specific mass (kg/m3)	Specific heat (kJ/kgK)	g-Factor	U-Factor
Floor	18.75	Carpet flooring	0.008	0.060	1300.0	0.20		
		Fibreboard	0.030	0.180	800.0	1.70		
		Noise insulation 040	0.030	0.040	75.0	1.03		
		Reinforced concrete 2400	0.100	2.500	2400.0	1.00		
		Air space	0.255	1.627	1.2	1.00		
		Sound insulation 040	0.030	0.040	75.0	1.03		
		Metal ceiling	0.001	50.000	7800.0	0.45		
Roof	19.15	Metal ceiling	0.001	50.000	7800.0	0.45		
		Sound insulation 040	0.030	0.040	75.0	1.03		
		Air space	0.255	1.627	1.2	1.00		
		Reinforced concrete 2400	0.100	2.500	2400.0	1.00		
		Cellular glass	0.080	0.040	105.0	1.00		
		Bitumen roofing membrane	0.005	0.230	1100.0	1.00		
		Gravel, sand, split fill	0.200	0.700	1638.0	1.00		
Interior walls	36.51	Sheet steel	0.001	50.000	7800.0	0.45		
		Insulation + stud	0.080	0.060	100.0	1.03		
		Sheet steel	0.001	50.000	7800.0	0.45		
Interior door	2	Timber-core plywood	0.025	0.130	500.0	1.60		
Exterior wall	7.39	Sheet steel	0.001	50.000	7800.0	0.45		
		Thermal insulation 035	0.090	0.035	10.0	1.03		
		Sheet steel	0.001	50.000	7800.0	0.45		
Window	5.13	Glass					0.64	1.4

Table 3 - Constructive parameters of thermal zone of type *L*. Source: Adapted from VDI 2078 (2015).

Construction element	Area (m2)	Layers	Thickness (m)	Conductivity (W/mK)	Specific mass (kg/m3)	Specific heat (kJ/kgK)	g-Factor	U-Factor
Floor	18.75	Floor covering	0.004	0.170	1200.0	1.40		
		Screed	0.040	1.400	1000.0	2.00		
		Air space	0.080	0.434	1.2	1.00		
		Reinforced concrete 2400	0.140	2.500	2400.0	1.00		
		Air space	0.300	1.627	1.2	1.00		
		Sound insulation 040	0.020	0.040	75.0	1.03		
		Metal ceiling	0.001	50.000	7800.0	0.45		
Roof	19.45	Metal ceiling	0.001	50.000	7800.0	0.45		
		Sound insulation 040	0.020	0.040	75.0	1.03		
		Air space	0.255	1.627	1.2	1.00		
		Reinforced concrete 2400	0.140	2.500	2400.0	1.00		
		Cellular glass	0.095	0.040	105.0	1.00		
		Bitumen roofing membrane	0.005	0.230	1100.0	1.00		
		Gravel, sand, split fill	0.200	0.700	1638.0	1.00		
Interior walls	36.51	Plasterboard	0.023	0.250	900.0	1.00		
		Insulation + stud	0.060	0.060	100.0	1.03		
		Air space	0.035	0.190	1.2	1.00		
		Plasterboard	0.023	0.250	900.0	1.00		
Interior door	2	Timber-core plywood	0.025	0.130	500.0	1.60		
Exterior wall	7.86	Concrete 2000	0.080	1.350	2000.0	1.00		
		Thermal insulation 035	0.080	0.035	10.0	1.03		
		Air space	0.030	0.163	1.2	1.00		
		Curtain panel	0.012	0.600	1650.0	1.00		
Window	5.13	Glass					0.64	1.4

Table 4 - Constructive parameters of thermal zone of type *M*. Source: Adapted from VDI 2078 (2015).

Construction element	Area (m2)	Layers	Thickness (m)	Conductivity (W/mK)	Specific mass (kg/m3)	Specific heat (kJ/kgK)	g-Factor	U-Factor
Floor	18.75	Floor covering	0.004	0.170	1200.0	1.40		
		Air space	0.040	1.400	1000.0	2.00		
		Screed	0.080	0.434	1.2	1.00		
		Reinforced concrete 2300	0.200	2.300	2300.0	1.00		
		Air space	0.255	1.627	1.2	1.00		
		Sound insulation 040	0.020	0.040	75.0	1.03		
		Metal ceiling	0.001	50.00	7800.0	0.45		
Roof	19.15	Metal ceiling	0.001	50.00	7800.0	0.45		
		Sound insulation 040	0.020	0.040	75.0	1.03		
		Air space	0.255	1.627	1.2	1.00		
		Reinforced concrete 2300	0.200	2.300	2300.0	1.00		
		Cellular glass	0.095	0.040	105.0	1.00		
		Bitumen roofing membrane	0.005	0.230	1100.0	1.00		
		Gravel, sand, split fill	0.200	0.700	1638.0	1.00		
Interior walls	36.51	Plaster 1300	0.015	0.570	1300.0	1.00		
		Vertical coring brick 1400	0.115	0.580	1400.0	1.00		
		Plaster 1300	0.015	0.570	1300.0	1.00		
Interior door	2	Beech, solid	0.025	0.200	800.0	1.60		
Exterior wall	7.39	Concrete 2200	0.080	1.650	2200.0	1.00		
		Thermal insulation 035	0.080	0.035	10.0	1.03		
		Air space	0.030	0.163	1.2	1.00		
		Curtain panel	0.012	0.600	1650.0	1.00		
Window	5.13	Glass					0.64	1.4

Table 5 - Constructive parameters of thermal zone of type *S*. Source: Adapted from VDI 2078 (2015).

Construction element	Area (m2)	Layers	Thickness (m)	Conductivity (W/mK)	Specific mass (kg/m3)	Specific heat (kJ/kgK)	g-Factor	U-Factor
Floor	18.75	Floor covering	0.004	0.170	1200	1.40		
		Screed	0.045	1.400	2000	1.00		
		Noise insulation 045	0.030	0.045	135	1.03		
		Reinforced concrete 2300	0.240	2.30	2300	1.00		
		Plaster 1300	0.015	0.570	1300	1.00		
Roof	19.15	Plaster 1300	0.015	0.570	1300	1.00		
		Reinforced concrete 2300	0.240	2.300	2300	1.00		
		Cellular glass	0.120	0.040	105	1.00		
		Bitumen roofing membrane	0.005	0.230	1100	1.00		
		Gravel, sand, split fill	0.200	0.700	1638	1.00		
Interior walls	36.51	Plaster 1300	0.015	0.570	1300	1.00		
		Vertical coring brick 1400	0.175	0.580	1400	1.00		
		Plaster 1300	0.015	0.570	1300	1.00		
Interior door	2	Beech, solid	0.025	0.200	800	1.60		
Exterior wall	7.39	Concrete 2200	0.120	1.650	2200	1.00		
		Thermal insulation 035	0.085	0.035	10	1.03		
		Curtain panel	0.012	0.600	1650	1.00		
Window	5.13	Glass					0.64	1.4

Table 6 - Constructive parameters of thermal zone of type *XS*. Source: Adapted from VDI 2078 (2015).

Construction element	Area (m2)	Layers	Thickness (m)	Conductivity (W/mK)	Specific mass (kg/m3)	Specific heat (kJ/kgK)	g-Factor	U-Factor
Floor	18.75	Floor covering	0.004	0.17	1200	1.4		
		Reinforced concrete 2300	0.300	2.30	2300	1.0		
		Plaster 1300	0.015	0.57	1300	1.0		
Roof	19.15	Plaster 1300	0.015	0.57	1300	1.0		
		Reinforced concrete 2300	0.300	2.30	2300	1.0		
		Cellular glass	0.120	0.04	105	1.0		
		Bitumen roofing membrane	0.005	0.23	1100	1.0		
		Gravel, sand, split fill	0.200	0.70	1638	1.0		
Interior walls	36.51	Sandstone	0.400	2.30	2600	1.0		
Interior door	2	Beech, solid	0.025	0.20	800	1.6		
Exterior wall	7.39	Sandstone	1.00	2.30	2600	1.0		
Window	5.13	Glass					0.64	1.4

ANNEX II - Hourly internal loads

Table 7 - Hourly internal load values. Source: Adapted from VDI 2078 (2015).

Hour	Number of persons	Lighting power (W)	Lighting convective fraction	Others power (W)	Others convective fraction
1	0	0	0	0	0
2	0	0	0	0	0
3	0	0	0	0	0
4	0	0	0	0	0
5	0	0	0	0	0
6	0	0	0	0	0
7	0	0	0	0	0
8	1	240	0.5	150	0.5
9	2	240	0.5	300	0.5
10	2	240	0.5	300	0.5
11	2	240	0.5	300	0.5
12	2	240	0.5	300	0.5
13	1	240	0.5	150	0.5
14	2	240	0.5	300	0.5
15	2	240	0.5	300	0.5
16	2	240	0.5	300	0.5
17	1	240	0.5	150	0.5
18	0	120	0.5	0	0
19	0	0	0	0	0
20	0	0	0	0	0
21	0	0	0	0	0
22	0	0	0	0	0
23	0	0	0	0	0
24	0	0	0	0	0

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APPENDIX

APPENDIX A - Simulation results of thermal zones of type *XL*, *L*, *S* and *XS*

Figure 10 - Operative temperature results for thermal zones of type *XL* (a), *L* (b), *S* (c) and *XS* (d). Source: The Author.

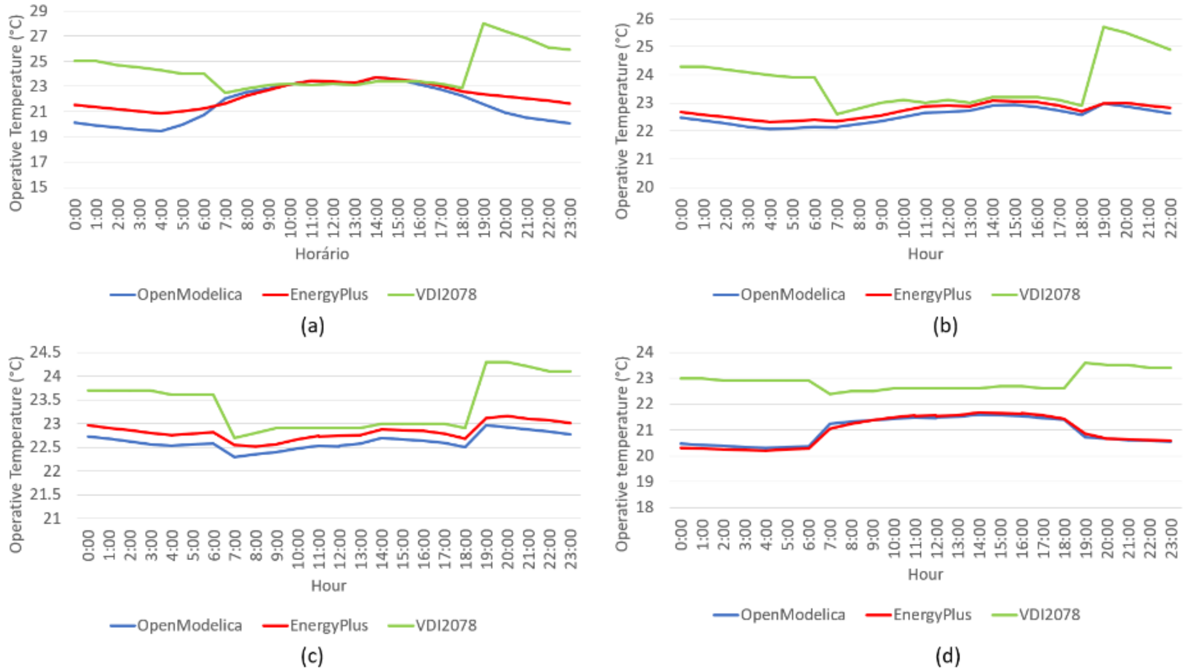


Figure 11 - Air temperature results for thermal zones of type *XL* (a), *L* (b), *S* (c) and *XS* (d). Source: The Author.

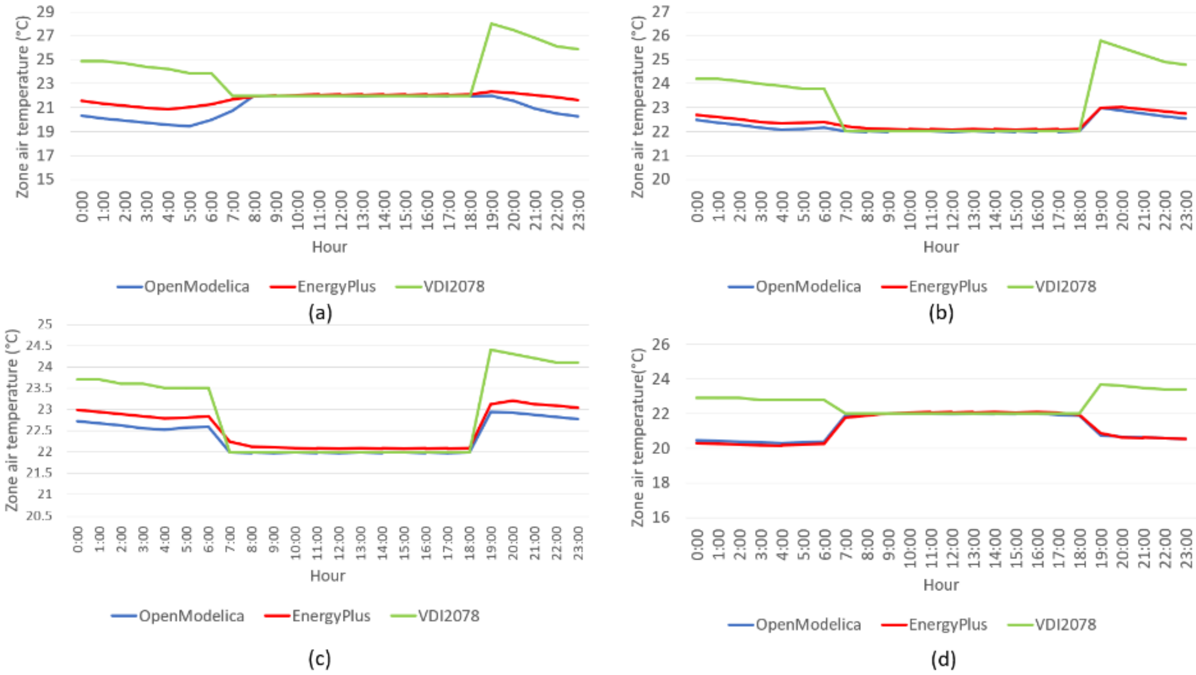
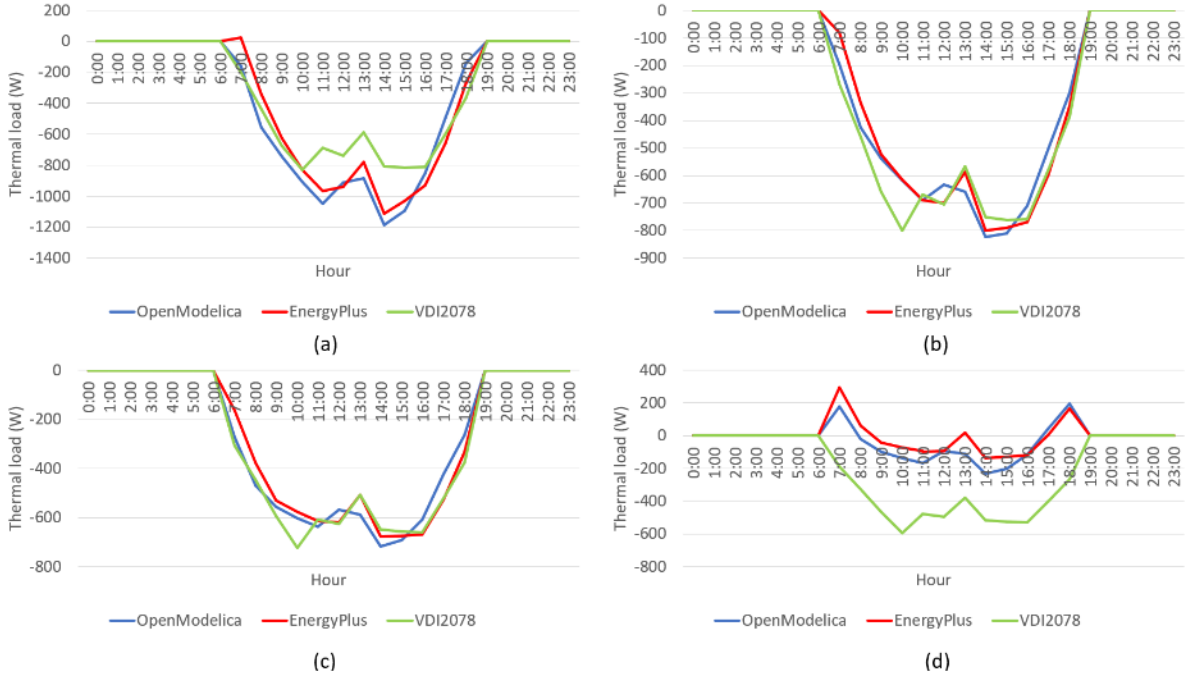


Figure 12 - Thermal load results for thermal zone of type *XL* (a), *L* (b), *S* (c) and *XS* (d). Source: The Author.



NOMENCLATURE

Symbols		
A	Heat transfer area	[m^2]
k	Heat conductivity	[W/mK]
Nu	Nusselt number	
Re	Reynolds number	
Pr	Prandtl number	
T_{ex}	External environment's temperature	[K]
C	Thermal capacitance	[J/K]
R	Thermal resistance	[K/W]
c	Specific heat	[J/kgK]
L	Wall thickness	[m]
T_i	Internal air temperature	[K]
T_{op}	Operative temperature	[K]
T_r	Mean radiant temperature	[K]
p	Radiant fraction	
α_{conv}	Heat transfer convection coefficient	[W/m^2K]
ε	Emissivity	
σ	Stefan-Boltzmann's constant	[W/m^2K^4]
α_{rad}	Heat transfer radiant coefficient	[W/m^2K]
ρ	Specific mass	[kg/m^3]

Abbreviations and acronyms	
VDI	Verein Deutscher Ingenieure
RC	Resistivo-capacitivo
ISO	International Standards Organization
TRY	Test Reference Year
IBPSA	International Building Performance Simulation Association
DIN	Deutsche Institut für Normung
TEASER	Tool for Energy Analysis and Simulation for Efficient Retrofit