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Coupling of Air Multizone and Thermal Multizone Models in Modelica

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ABSTRACT

Building simulations are used to investigate building performance and design the building systems optimally. In particular, the air exchange between zones and with the environment has a pivotal role in modern ventilation system design. Nevertheless, the model of the airflow becomes difficult for the modeler, motivated by the complexity of the grid that has to be modeled. IDEAS, a Modelica library, includes components for thermal multi-zone models of buildings as well as models for heating, ventilation, air conditioning and other elements that interact in the same model. The actual version, however, does not include proper components to model airflows in an efficient way. The simulated air includes humidity and several trace substances, but the detailed transportation of those substances between the zones currently does not exist in the standard components. The purpose of this paper is twofold. At first, the article intends to describe the development of new components that will be used to implement the air multi-zone model into the existing thermal multi-zone model in IDEAS. The second goal is to integrate the newly developed components with the actual components of the library to share parameters that are needed to generate a grid of air pressure, reducing the modeling steps. The developed components are based on the pressure difference of the connected elements and include vertical air shafts, orifices, infiltration defined by the effective air leakage area, windows and doors.

Keywords: Modelica, IDEAS library, building simulations, Multi-zone airflow, contaminant transport

INTRODUCTION

Building simulations have become more and more complex in recent times. The computational capacity of computers permits more extensive simulations of detailed models that can be formed out of individual sub-models that analyze different aspects of the same building. Moreover, the sub-models can exchange common parameters while the simulations will reflect the consequent interactions between them. In TRNSYS (Klein S.A. et al. 2000), the airflow network is added in parallel with the thermal model of the building (Weber, Andreas et al. 2003), but every element has to be defined manually in both sub-models, meaning that the exchange of information is very limited. This double modeling requires more effort and time from the user, who has to provide redundant information and has to manually check the consistency between the components in both sub-models, increasing the risk of making mistakes. EnergyPlus can integrate airflows (Gu, Lixing. 2017) in the constructive elements, solving the mentioned problems, through relationships defined between the different modules in the tool. The software ESP-r can also integrate airflow networks in the components, which are represented graphically, being quite intuitive for the modeler.

CONTAM (Building and Fire Research Laboratory 2015) is a software used for modeling multizone indoor air quality (IAQ) and ventilation. However, even though the software represents a powerful tool to simulate the interzonal air exchanges, it is incapable to simulate a detailed thermal behavior of the building, which requires an extensive number of parameters such as the physical properties of the construction elements, the orientation of each surface, etc. The result is a model that interacts well under the defined conditions, which are not the same as in the thermal model.

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Furthermore, the user cannot design or implement any additional component, which represents one of its most important limitations.

Modelica (Hilding Elmqvist 1997) is an object-oriented modeling language. It allows modeling of different kinds of fluid, electrical, mechanical or other sorts of systems and establishes relations between them. Modelica is also an acausal language, which means that the equations are not interpreted as assignments, but as equalities. This property lets the combination and extension of the models of different kinds. Such properties make Modelica to be considered as an appropriate solution to increase the flexibility and interactivity that complex building simulations require.

IDEAS (Jorissen et al. 2018) is a Modelica library that contains different components to make models of buildings. It is based on Buildings library while both libraries come from the IBPSA Project 1 (M. Wetter et al. 2019). According to the developers of IDEAS, the library is focused on simultaneous transient simulations of thermal and electrical systems. It also includes components for infiltration and air quality, but without the interaction between the zones (unlike the models CONTAM). However, since IDEAS library contains models that are coded in Modelica, it becomes possible to extend and combine those models with other available Modelica libraries that already include the missing calculation methodology. In this way, the developer is encountered with already made models that can serve as a solid base for integrating the complete physical phenomena of any kind, such as air quality.

In this article, the methodology for extending the components of IDEAS 2.1.0 modeling library in order to include the accurate modeling of multizone indoor air quality coupled with the thermal model will be described. The resulting components are integrated into the same structure as the original ones. The simulations are executed in the Dymola 2020x.

MULTI-ZONE MODELS

The fundamentals of the developed models in IDEAS library and CONTAM software tool are based on the same principle. They represent the zones as single nodes in the center of the zone with uniform properties of the entire volume. Each zone is defined by the air volume confined in its boundaries, which are the walls, floors, windows, etc. The interactions of the zones with the rest of the components in the model are reduced to the interactions with the node that represents the entire zone and the components that influence it.

Thermal Model of the Building Envelope

In IDEAS, each zone is made out of constructive elements of the building, such as walls, floors, and windows. Those elements are modeled as combinations of thermal resistors and capacitors which are parameterized according to the physical properties of the construction materials. The models are connected by heat transfer equations, as convective heat and radiative heat, but they cannot transfer mass, so they cannot be used to include air transferences. Besides the constructive elements, zone models feature out of different ports which among other properties, can be used to inject heating energy coming from the heating system or the heat produced by the defined occupation profiles. Moreover, each zone has two specific ports (one inlet and one outlet) to include ventilation systems, so by default, there are only two connections that can exchange mass with the zone. The ventilation ports can be used to interconnect zones, but the number of connections is limited to two.

On the other hand, the zones have an internal component that can emulate the infiltration. The component exchanges air with the exterior, which is a boundary condition defined by a weather file. The exchange of the air is not interzonal and any incoming air will have the properties of the exterior.

Airflow Model of the Building Envelope

In CONTAM, the zones are also presented as nodes delimited by user-defined boundaries in the interface. The modeler can define two types of connections between zones, which can exchange air from one zone to another. One of these two types of connections is the airflow paths which depend on the geometry of the zones. These connections

represent openings like doors, cracks or infiltrations between zones and they are limited by the geometry of the floorplan, such as walls or floors. The other type of available connectors are ducts, that can be defined without geometrical restrictions. These connections are normally used to implement ventilation systems in the model. Both types of connections have specific parameters that exhibit the stream of the flow through them (roughness, power-laws, etc.). The airflow models also include weather conditions, but the only transmitted energy is the one that goes with the exchanged air with the exterior.

COUPLING THERMAL AND INDOOR AIR QUALITY MODELS

In this work, the existing models made in IDEAS will be enhanced by similar components developed within CONTAM tool. Buildings library (Michael Wetter et al. 2014) includes some components for infiltration that were validated with the equivalent elements in CONTAM (Michael Wetter 2006). They were also included in IDEAS in the package *IDEAS.Airflow.Multizone*. The components that control the airflow are the following:

1. DoorDiscretizedOpen
2. DoorDiscretizedOperable
3. EffectiveAirLeakageArea
4. Orifice

These components can be used to represent the airflows through cracks, doors, windows, staircases and similar elements. They are based on power law relationships that calculate the airflow depending on the pressure difference in both sides of the component. A detailed insight into the calculation methodology can be found in (Michael Wetter 2006). The components have different input parameters that need to be given in order to define the component. Some of those parameters are leakage area, flow exponent or the type of medium (air with possible trace substances). The components also have an even number of fluid ports that are used to calculate the pressure drop in both sides of the component and to exchange the mass flow calculated with the power law. To have an adequate performance of the components it is necessary to have realistic values of the pressure on both ports of the component.

The absolute pressure of the zones in IDEAS depends on the initial conditions and the connections with the two ventilation ports and also the class selected for the inner component *interzonalAirFlow*, which defines a general infiltration for the zone. This component can also force the zone to have the same pressure as the weather conditions if the classes *FixedPressure* or *n50FixedPressure* are selected. As said before, the component does not represent a realistic interzonal airflow, so it has to be neglected by choosing the class *AirTight*. In this case, the only references for the absolute pressure in the zone are the initial conditions and the ventilation ports, which should not be used to determine the absolute pressure of the zone.

Addition of Extra Fluid Ports and Elevation to the Zone Model

As the fluid ports of the zone are specific fluid configured ports defined within Modelica Standard Library, all connections will be reduced according to the energy and mass balance equations contained within those ports. Figure 1 illustrates an example of the undesirable behavior that may happen when these ports have more than two connections (equations) and not all of them have the same flow direction. *Port_b* has two external flows (m_1 and m_2) that are canceled in the port ($m_1 = m_2$). Those flows should be connected directly to the node that represents the zone. *port_a* has also two flows (m_3 and m_4) but they can effectively reach the node of the zone because the flow direction is the same. To solve the problem, more ports have to be added to guarantee all flows are connected to the node of the zone.

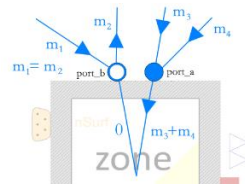


Figure 1 Example of multiple flows connected to the ventilation ports of a zone model.

The component in the zone *AirModel* has been edited to include several ports which will act as a bridge with the node of the zone. The resulting zone component is shown in Figure 2.

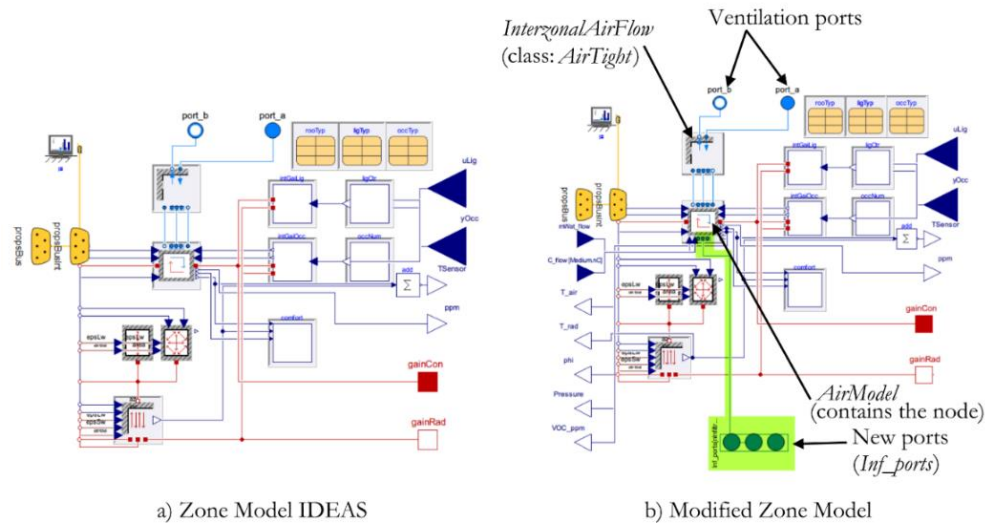


Figure 2 a) original zone model in IDEAS b) Modified model to include ports for the airflow components (highlighted in green).

Note that in Figure 2 other elements were added to measure different values and to add different trace substances to the zone. This paper will only focus on the structural changes required to implement the coupling properly, so the additional components will not be considered here since they are not essential for the implementation.

Definition of the pressure levels

The pressure in a zone is represented by the pressure in its node, which is centered in the zone. In reality, the hydrostatic pressure in the zone varies according to the vertical height, due to the weight of the fluid that is above a certain point in the zone which is typical for any fluid under the influence of the gravity force. To consider the pressure at a different height of the center of the zone it is necessary to use the component *IDEAS.Airflow.Multizone.MediumColumn*. This component calculates the pressure difference between a defined reference point and the pressure above or below that point, separated a defined height. It uses the density of the fluid and the distance to calculate the pressure difference between the points. This component will be used to calculate the actual pressure difference in the airflow components and it will be used to define the correct pressure relationships between zones that are at different heights (or altitudes). In other words, it will define which zones are above or below others by connecting their nodes. The interconnection of different zones (including the exterior) will generate a network of pressures. The nodes in the network are the ones in the zones and also the points defined by the *MediumColumn* components.

Containers for airflow components

To simplify the generation of the pressure network, the *MediumColumn* components are integrated with the components that control the airflow into models that contain them. There are three types of containers, depending on

the use. One is designed for horizontal infiltration and openings like staircases (*CrackModelFloor*). The second one is designed for infiltration in non-horizontal components like walls or windows (*CrackModelWall*). The last type can be used for non-horizontal openings, like doors or windows (*Door*). Those containers can be connected directly to the zones through the fluid ports. Figure 3 shows the structure of the three kinds of containers connected to example zones, showing the power-law components connected to the medium columns with annotations about the height of them.

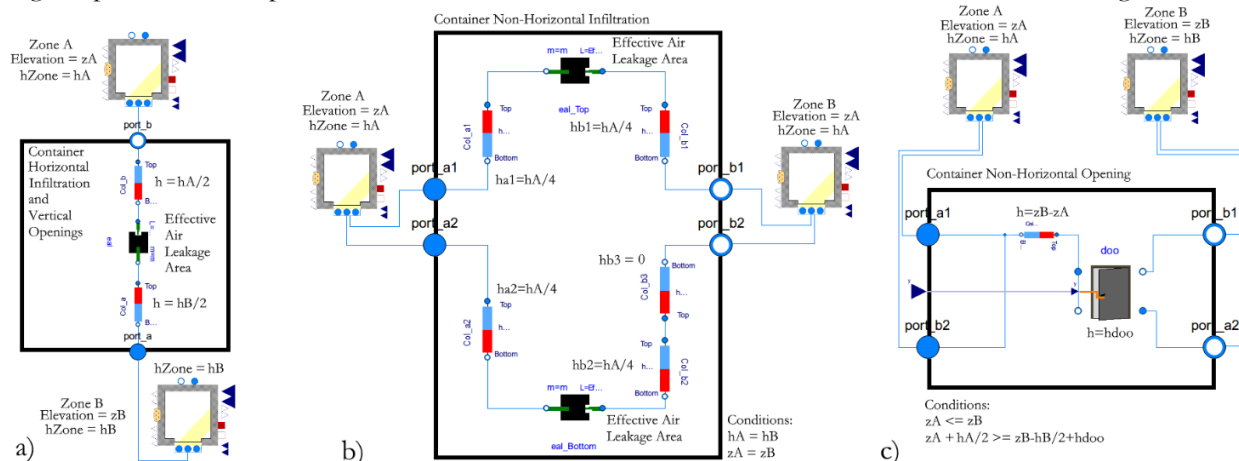


Figure 3 Inside the black rectangles there are (a) a container for horizontal infiltration and openings (*CrackModelFloor*), (b) a container for non-horizontal infiltration (*CrackModelWall*) and (c) a container for non-horizontal openings (*Door*). All of them are connected to example zones.

There are two restrictions on the use of each non-horizontal container. The one for non-horizontal infiltration requires that the zones on both sides (called Zone A and Zone B) have the same height ($h_A = h_B$) and also the same elevation ($z_A = z_B$). The elevation is the absolute height of the zone (or any other element) respect to the reference level. The container is not able to connect zones with different heights and elevations. Nevertheless, it is possible to connect the side B of the component (*port_b1* and *port_b2*) to the boundary conditions determined by the weather file, specifying the elevation of the Zone A. In this case, the column *Col_b1* will have its characteristic height of $h_A/4 + z_A$ while the column *Col_b3* will have the value of the elevation of the Zone A (z_A). The elevation of the weather conditions is 0 to simplify the expressions.

In respect to the container for non-horizontal openings, the restrictions require that the zone connected to the side A (*port_a1* and *port_b2*) must have the same or a lower elevation than the other zone ($z_A \leq z_B$). On the other hand, the elevation of that zone plus its half-height has to be equal or lower than the elevation of the other zone minus its half-height plus the height of the opening element ($z_A + h_A/2 \geq z_B - h_B/2 + h_{doo}$). In this case, it is also possible the connect the zone to the exterior, which has to be connected to *port_a1* and *port_b2*.

However, it is important to emphasize that it is possible to model cases that are not allowed in the containers by using the contained elements separately, but the number of connections and the parameters that have to be manually set increases considerably. The reason to use containers is the easiness of modeling the most common configurations.

Boundary containers

Another kind of container has been created to link the properties of the airflow components to the boundary surfaces. There are two types of containers: one for walls and another one for windows. In this way, the modeler is able to choose only three types of components to build a model of a building, which are the modified zone model, the wall container and the window container. All the parameters of the contained models can be easily accessed from the parameters dialog of the boundary containers. In Figure 4, the connections of both types of containers to the zones may be seen.

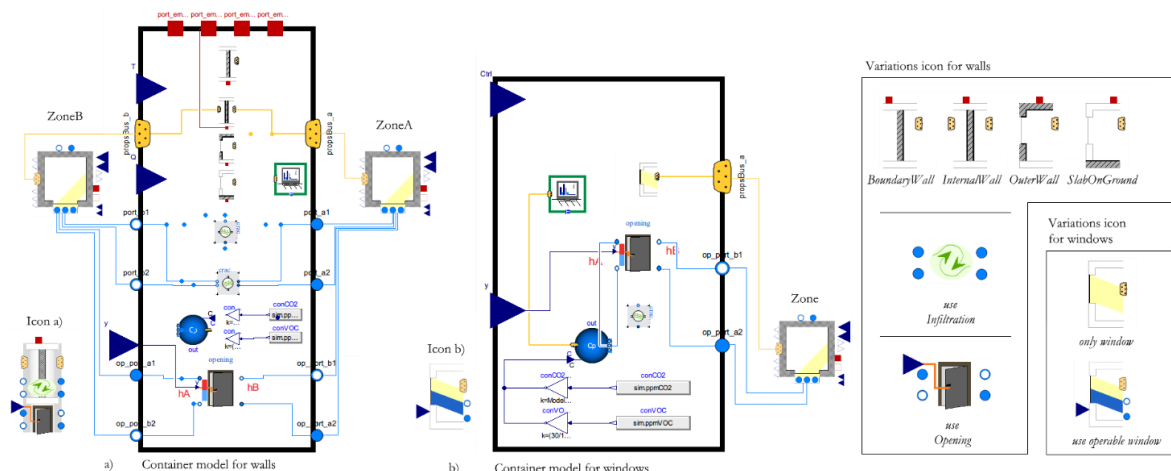


Figure 4 The black rectangles contain (a) a container model for walls and the (b) a container model for windows. They have options to select a certain wall type (a) and to use or not infiltration (a) or openings (a and b). On the right, there are different graphic elements that are activated depending on the selected parameters of each container.

The wall container is consistent out of all the possible wall models in IDEAS (*BoundaryWall*, *InternalWall*, *OuterWall* and *SlabOnGround*) and all possible containers for airflow (*CrackModelWall*, *CrackModelFloor* and *Door*). The container also includes a boundary condition with the properties of the weather and details over the orientation of the surface (*Outside_CpLowRise*). All the elements and the connections are conditional, depending on the value of certain parameters to define the type of wall and the inclination of the surface. When a set of options is selected, the non-used classes are removed from the model. Furthermore, the graphical elements and the unnecessary options are disabled, so the modeler will have a clear view of what it is being used all the time. The connections with the zones are made with the *propsBus* (the connectors originally from the components in IDEAS) but the fluid ports for the pressure model have to be connected individually to the zones.

On the other hand, the windows container includes the window model (*Window*), the model for non-horizontal openings (*CrackModelWall*), the model for horizontal openings (*CrackModelFloor*) and a boundary condition for the weather (*Outside_CpLowRise*). As in the other container, there are conditional components and connections while some parameters are shared by the different elements.

Boolean Flags in the SimInfoManager

The *SimInfoManager* of IDEAS has been extended to include two flags (*useOpenings* and *useInfiltration*). In this way, the modeler can enable or disable the infiltration elements and the openings. By default, the containers refer to those flags, but they can be set individually by the modeler. With those flags, the modeler can easily remove the infiltration model or/and the openings. If the modeler decides not to use any of them, the model will react the same as if it was modeled with the original components of IDEAS since all airflow models would be removed from the model. Then, the original infiltration models of IDEAS can be used, which are simpler and also faster concerning the simulation time.

TEST MODEL

All components created or modified in the previous chapter are used in the model of a detached house showed in Figure 5. Every single surface exposed to air on both sides has infiltration, including roof, external and internal walls. The surfaces in contact with soil do not consider infiltration. All connections for the pressure network and *propsBus* connections are hidden.

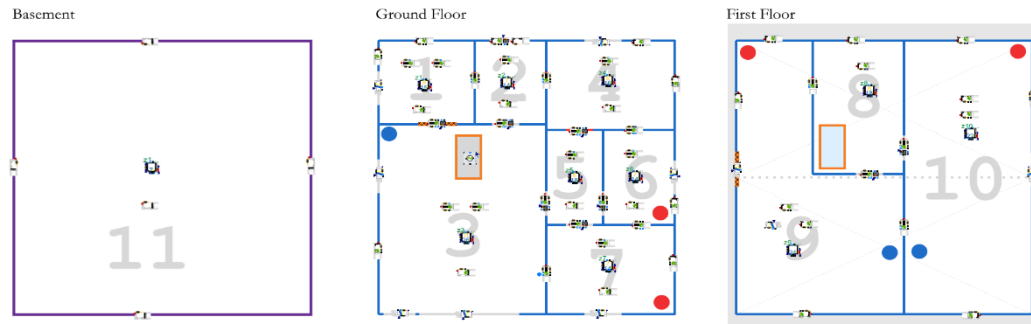


Figure 5. Model of the envelope of the house detached house. The floor plan was included in the model as a graphical element to easily understand it.

The elements used are 11 modified zones, 57 wall containers, 10 window containers and a container for horizontal openings (*CrackModelFloor*), which is used for the staircase. The connections between elements are hidden to not disturb the view. The model includes flags to enable the use of infiltration components, use exterior openings and interior openings. There are 188 connections the modeler has to establish for the pressure network and 98 manual connections for the *propsBus* used by IDEAS components.

Test Simulation: Trace substances with thermal influence. Air with a baseline CO₂ concentration of 400 ppm at 20 °C was injected at 0.1 kg/s to the zone 7. At the same time, the air is being extracted from the zone 10 at the same constant flow rate of 0.1 kg/s. All the interior doors and openings are open, while the exterior door and windows are closed. All infiltration components are enabled. During the simulation, a pulse of 1 ppm was added to the baseline CO₂ concentration of the injected flow for 4 hours, as shown in Figure 6. One hour after this change, the temperature in the injected air increases up to 40 °C for four hours as well to illustrate the influence in the concentrations. The results show variations in the CO₂ concentration of the zones along time and because of the temperature changes. The zone 11 (the basement) does not have any wide opening, so the CO₂ concentration variations are quite low respect to the other zones.

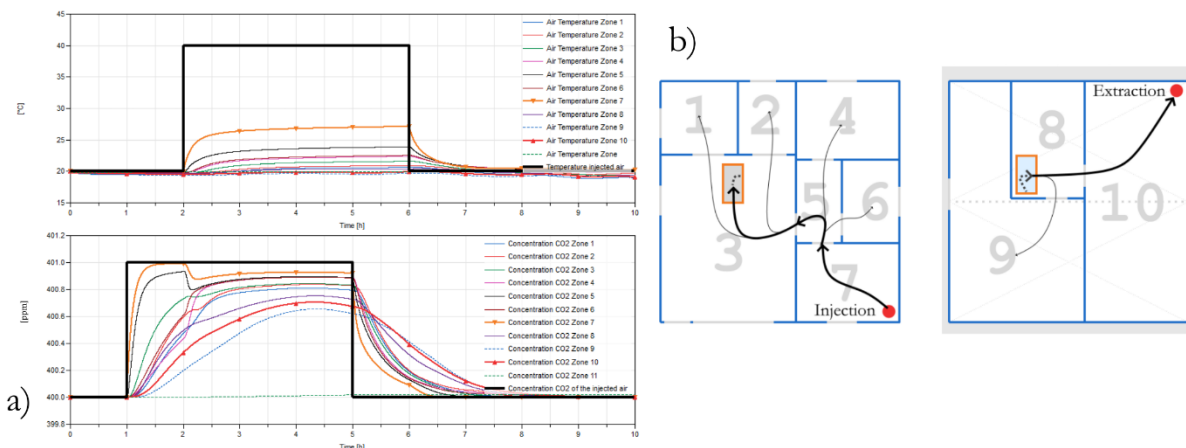


Figure 6. The (a) Air temperature and CO₂ concentration profiles of the zones. The flow paths are shown in (b). The basement is not represented in (b).

Test Simulation: Speed. The envelope has been tested by including it in a model that represents a blower door test. A constant pressure drop of 50 Pa (overpressure tests) has been set in the zone 2, which represents the entry of the house. Two simulations were executed under the same conditions. While one had all the components enabled, the other one had all the airflow components disabled. The only difference was the value of the flags that enable the airflow components. In both cases, the selected solver was ccode (tolerance 10⁻⁷) and the simulated time was 10 days. The simulation with all airflow components finished after 23.43 seconds while the model without airflow components needed 4.33 seconds (less than 20 % of the time of the other simulation).

FINDINGS

The container models for walls and windows are helpful for the modeler because they reduce the number of manual connections that have to be made with the zones. Nevertheless, the fluid ports can be integrated into the *propsBus* to reduce even more the manual connections, which can cause modeling errors. The airflow model can be neglected easily from the original thermal model by using the flags. The final model is similar to a model created with the components in IDEAS library. It is not possible to remove the thermal model and simulate only the airflow model since the zone belongs to the thermal model and it cannot work without thermal components. The simulation speed is drastically affected by the airflow model, which implies the importance of using the flags. It was noted that some solvers have difficulties to simulate the model. A similar problem was also reported by the work of (Dermont et al. 2016). Single-step solvers work better for the airflow model (an example is Radau IIA). The solver ccode is multi-step in the used software, so to compensate for the difficulties during simulations the tolerance has to be decreased.

CONCLUSION

In this article, the coupling of the thermal model and the airflow model was explained. The described methodology exhibits the possibility to build a model with a few components and have the option to neglect the airflow model. Nevertheless, the airflow components can be integrated into the wall and window components in IDEAS, and the flow ports included in their *propsBus*. As part of the future work, the presented model will be verified on other cases and it will also include the cases that do not satisfy the requirements for the non-horizontal containers which are, at the moment, zones with the same elevation and height. The resulting components will be accessible through an online repository to help interested researches and general public.

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