SIMULATION SPEEDUP TECHNIQUES FOR COMPUTATIONALLY DEMANDING TASKS

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ABSTRACT

The computational cost for the repeated evaluation of zonal-type building simulation models can be prohibitive especially in contexts, such as Building Optimization and Control Design, where repeated evaluation of the models — for different initial and boundary conditions — is required. In the present paper, two techniques to reduce simulation time are investigated: (i) geometry simplification for periodic geometries; and, (ii) the use of co-simulation to split a building into simpler sub-buildings, that can be evaluated in parallel, exploiting the resources of multi-core computational architectures. These simulation speed-up approaches are evaluated, with respect to accuracy and computational effort, against the validated full-scale models of two real buildings.

INTRODUCTION

The high complexity of building simulation stemming from the requisite information, including actual climate data, geometries, building physics, HVAC-systems, energy generation systems, natural ventilation, user behavior (occupancy, internal gains, manual shading) to name but a few, makes the development of accurate simulation models a challenging task. It is becoming quite common, especially during the design (or subsequent retrofitting) phases of a building lifecycle, that simulation models are employed to prognosticate energy performance and help identify underlying problems with respect to energy design. The calculation methodologies used can range from "simple" quasi-steady-methods (13790, 2008) to dynamic, implemented in energy-performance simulation zonal-type software like EnergyPlus (Crawley et al., 2001) and TRNSYS (Klein et al., 1976). Each calculation method supports different use cases and, as such, the modeling assumptions and the associated inputs can vary greatly in the levels of detail and information that has to be provided. The zonal approximation is acceptable for many envisaged and practical use scenarios, as it manages to strike a balance between accuracy and computational complexity.

Beyond the zonal-paradigm approaches, models developed specifically for a particular purpose (e.g. control design) exist. For model-based control design purposes, typically state-space models adhering to certain mathematical constraints are required. The accuracy of such models may not be of essence but rather their ability to correctly capture dynamics and sensitivities of the system that is being modeled, as this is the critical quality needed for control design. For computational efficiency, the number of states should be "small," as repeated evaluations might be required within the control design context where they will be applied. In the building application domain, the development of such models remains an open problem (Prívara et al., 2012). Towards defining such models many approaches are possible. The simulation models can be developed using first principle approaches (Lee and Braun, 2008; Oldewurtel et al., 2012; Sturzenegger et al., 2012), but for larger buildings their construction is impractical, due to the increased complexity (Prívara et al., 2011). Data-driven models, produced by system identification methods (Kolokotsa et al., 2009; Váňa et al., 2010), can be viable approaches, but still it is very often that the identification process fails when applied on real, occupied buildings, due to under-excitation of system dynamics (Váňa et al., 2010). In more recent approaches (Prívara et al., 2011) a full scale, zonal-type, thermal simulation model of the building is used for the identification phase, which remains computationally expensive. What is particularly attractive in this approach is that excitation necessary for the identification happens at the simulation level, so it is possible to excite the system in many ways that would be impractical, or even unrealistic, if they were to be applied in the real building. As can be inferred from the discussion above, the use of simplified models that are highly computationally efficient can be a viable option. When accuracy and computational effort constraints are present, simulation speed-up techniques like the ones discussed in this paper, can yield a good trade-off between accuracy and computational complexity. Even though for small buildings, full scale models have been used successfully for model assisted control design (Giannakis et al., 2011; Kontes et al., 2012), field studies (Hong et al., 2009) have shown that, for large buildings a very detailed model is impractical to simulate, since it is too complex and takes too long to run. Simulation is predominantly slowed down by the increasing number of zones, windows and surfaces and, as such, simulation speedup techniques should focus on geometry reduction approaches.

In the present work, the efficiency of two simulation speedup techniques is investigated for two buildings:

the Centre for Sustainable Building of the Fraunhofer Institute for Building Physics (FIBP), located in Kassel, Germany, simulated using TRNSYS; and the second is the Technical Services Building at the Technical University of Crete (TUC), located in Chania, Greece, simulated using EnergyPlus. The proposed speedup approaches are evaluated on the two demonstration buildings, with respect to the accuracy of the simulation results and their impact (positive or negative) to the computational effort. Towards investigating the accuracy, both the detailed and reduced model of the two buildings are simulated for a certain time interval and the temperature deviation is selected as the accuracy measure. For the simulation speedup on the other hand, scenarios with different run periods are investigated and the respective speedup times are presented. In all cases, the speedup models exhibit significantly reduced execution times.

FULL-SCALE ZONAL-MODEL

According to building thermal simulation zonal-models, a full-scale building consists of one or more thermal zones which are coupled with each other and with the environment. A zone consists of an air volume of a uniform temperature and all surfaces bounding or inside that air volume. The basis for the zone air temperature estimation is the formulation of energy and moisture balances for the zone air and the solution of the resulting ordinary differential equations.

Using a Predictor/Corrector approach, the simulation engine (ASHRAE Handbook, 2009; TRANSSOLAR, 2010) calculates the actual zone mean air temperature. The fundamental idea is to use an iterative method: first, predict the air system load needed to reach the desired temperature (predictor); second, simulate the air system to determine its actual capability of achieving this temperature (corrector); and, finally, reconfigure the zone air heat balance to calculate the achieved zone mean air temperature. An identical process is performed to calculate the actual zone mean air humidity.

A consequential aspect of the overall solution scheme, is the definition of the heat balance equation at each face of a building construction component (wall, roof, floor, etc.). The heat balance on interior faces, which are not exposed to outdoor environmental conditions, can be written as follows:

$$q_{lw_i} + q_{sw_i} + q_{sol_i} + q_{k_i} + q_{c_i} = 0; \qquad (1)$$

where, q_{lw_i} is the sum of the longwave radiant exchange transfer between zone surfaces and the longwave radiation transfer from equipment in zone; q_{sw_i}, the shortwave radiation transfer to surface from lights; q_{sol_i}, the transmitted solar radiation flux absorbed at surface; q_{k_i}, the conduction transfer through the wall; and, q_{c_i}, the convective heat transfer to the zone air. External surfaces boundary conditions (external boundary conditions) are derived by Equation 2

and have the major impact to unsteady heat transfer through building elements, since they are affected by variable weather data.

Similarly, the heat balance on exterior faces, exposed to environmental conditions, is expressed as follows:

$$q_{lw_o} + q_{sol_o} + q_{k_o} + q_{c_o} = 0; \qquad (2)$$

where, q_{lw_o} is the longwave radiant exchange with the air and surroundings; q_{sol_o}, is the absorbed solar shortwave radiation flux; q_{k_o} is the conduction transfer into the wall; and, q_{c_o}, the convective transfer to the outside air. Each simulation engine incorporates the appropriate mathematical models to quantify each term of Equations 1 and 2. These models, use available (geometric and weather) data, to derive proper boundary conditions. Both full-scale simulation models, described below, use Equations 1 and 2 to provide realistic boundary conditions at each simulation timestep.

FIBP Building

The FIBP building is the office building of the Centre for Sustainable Building in Kassel, situated at the University of Kassel, Germany. The building consists of 26 rooms, spanned in three floors and each physical room has at least one corresponding thermal zone in the full scale model.
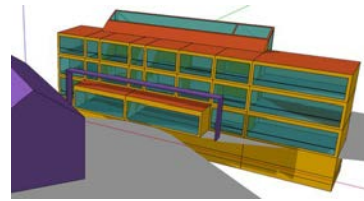

Figure 1: FIBP building – full-scale simulation model

The full-scale model of the FIBP building has been set up in Trnsys 17 using Google SketchUp with the purpose to hold the option of employing the detailed radiation mode that is provided with Trnsys 17. To meet the requirements for the detailed radiation mode, all zones have to be convex, i.e. every wall of a zone has to be in the line of sight with all other surfaces of the zone. This can only be accomplished by slightly simplifying and modifying the original geometry of the model.

TUC Building

TUC building is of triangular shape and comprises 10 office rooms, an open meeting space, two corridors (one in each floor), the main entrance, an equipment room, a toilet and a basement that is used as a storage area. In both floors (ground floor and first floor) there is a central corridor running the length of the building with offices on either side. In the middle of the corridor there is an open meeting space of semicircular form. The plan of the first floor is similar to the ground floor, with the only difference the presence in the first floor of a semicircular atrium to connect the ground floor meeting space with a large glazing on the roof.
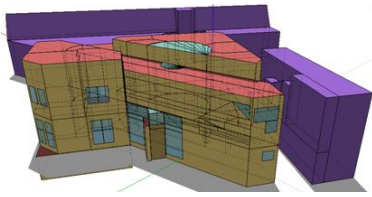
Figure 2: TUC building – full-scale simulation model

For energy performance tasks, a full-scale thermal simulation model has been developed in EnergyPlus. The representation of the building geometry was created according to the floor plans using the Google SketchUp plugin, Openstudio – see Figure 2.

The presence of the solar atrium, along with the radiation model used, gives an uneven heat distribution between the simulation and reality. For this reason, each corridor is split into more zones, so that the solar gain and radiant exchange effects can be correctly captured is necessary, increasing the number of zones by eight. For a detailed description of both full-scale thermal simulation models, refer to (Dröscher et al., 2010, 2011).

MODEL SPEEDUP TECHNIQUES

Despite the fact that full-scale building simulation models are available, they are not suitable for computationally demanding tasks, such as model assisted control design, for which purpose the present simulation models are created. Since high complexity and prohibitive simulation runtime are predominantly due to the full-scale, detailed, geometry representation of the demonstration buildings, geometrical model reduction approaches are required. In such cases, a commonly used approach is to define a representative building block, cut-out from the full-scale geometry representation and able to reproduce the whole building. Its walls where actually other zones adjoin are defined as "boundary walls".

A significant difficulty of this approach is to determine proper boundary conditions at each boundary wall, as they are naturally derived by the heat balance equation on a boundary wall. The heat balance equation on exterior faces, described by Equation 2, remains valid. However, it is the heat balance on interior faces, corresponding to a boundary wall, that deviates from the one formulated by Equation 1.

For these faces, two types of boundary conditions could be defined:

- *Adiabatic boundary condition* - is a special case of *Neumann* conditions, where the surface is assumed to be perfectly insulated. Thus, any heat transfer through boundary walls is excluded:

$$-k\left(\nabla T \cdot \mathbf{n}\right) = 0. \qquad (3)$$

- *Dirichlet boundary condition* - describes a situation for which the surface is maintained at a fixed temperature T_{sch} at each simulation

timestep. The boundary condition is formulated as:

$$T_{so} = T_{sch}. \qquad (4)$$

FIBP Building

As detailed simulation of indoor temperatures of the full-scale model increases computational complexity, a "tower" of three offices upon each other is cut-out, since the whole building can be viewed as a parallel expansion of the simple "tower" sub-model in one dimension. Here, the outer surfaces are actually adjoining rooms surfaces, which are defined as "boundary walls" and the adjacent constructions that have a shading effect on the tower but are not included in the thermal simulation are modeled as shading groups. The tower is shown in Figure 3.
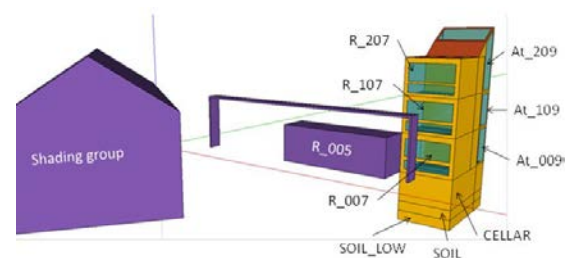

Figure 3: FIBP building – tower simulation model

The tower concept is preferred against a horizontal cut-out to keep the essential effect of vertical temperature stratification.

Initially, a *Dirichlet* boundary condition with variable temperature and fixed at each simulation timestep is supplied as boundary condition for each wall. In this case, the boundary condition at the outer plane of contact surfaces is defined by Equation 4, where, the temperature schedule for the outer plane of a boundary wall (T_{sch}), is the actual room temperature of adjoining rooms available from measurements. This approach has limited perspective from a practical point of view, since forecast simulations would require predictions of the temperatures in the adjoining rooms, which there is no chance to be available. Since room temperature trajectories are to be simulated by the model this would be a vicious circle.

Using an *Adiabatic* boundary condition, the aforementioned hindrance can be overcome; however, there are cases, such as the tower operating differently from the rest building, that the assumption of a zero heat transfer could lead to an over- or underestimation of the zone air temperatures.

TUC Building

For the TUC building on the other hand, its triangular geometry does not define a building block, like the concept of "towers" above, being able to reproduce the whole building, so the periodicity/adiabatic technique can no longer be applied. In this case, an alternative option would be to divide the building into three sub-buildings, each of which can be simulated

separately establishing the connection by using compatible *Dirichlet* boundary conditions. Such splitting of the building, along with the parallel simulation in existing multi-core computer architectures, can yield a sizable reduction in simulation run-time. The use of co-simulation, described next, can yield an effective method, for the transfer of boundary conditions between the sub-buildings, establishing their thermal interaction. For the particular case at hand, the TUC building, since the two main corridors (that include the attrium) are connected through horizontal holes, the need for correctly computing radiant gains in the attrium, forces including the corridors in one of the sub-buildings. With this prerequisite, the whole building is divided to three sub-buildings, shown in Figure 4.

Regarding the boundary conditions, a first approach would be to use similar *Dirichlet* boundary conditions, to that applied to the "tower" of FIBP building (adjacent rooms temperature). A more complex approach would be to force as boundary condition for each sub-building contact surface the temperature of the corresponding surface, resulting from the adjacent sub-building's simulation. In other words, suppose that wall A is a common surface of sub-buildings 1 (A_1) and 2 (A_2). Then, at the end of sub-building:1 simulation, the temperature profile of surface A_1 is applied as boundary condition to surface A_2 so as to simulation of sub-building:2 run. Thus, a set of *Dirichlet* boundary conditions needs to be defined.

Aiming at control the temperature of a surface that is adjacent to an area that is not included to the simulation model (part of a boundary wall), "OtherSideCoefficients" feature in EnergyPlus (DOE, 2010) is used. Other side coefficients affect the other side of a surface as follows:

$$T_{so} = c_1 T_z + c_2 T_{sch} + c_3 T_a + c_4 T_g + c_5 T_a v_w; \quad (5)$$

where, T_{so}, T_z, T_{sch}, T_a, T_g and v_w refer to the surface temperature, the temperature of the zone being simulated, the dry-bulb temperature of the outdoor air, the temperature schedule for the outer plane of the surface, the temperature of the ground and the outdoor wind speed, respectively. Here, a temperature profile (T_{so}) is provided as boundary condition.

In the present work, the boundary condition at the outer plane of each boundary wall is defined by equation 5, with the following coefficients' combination: $c_1 = 0$; $c_2 = 1$; $c_3 = 0$; $c_4 = 0$; $c_5 = 0$; where, the temperature schedule for the outer plane of a sub-building boundary surface (T_{sch}) is the temperature profile of the inner plane of the corresponding surface of the adjacent sub-building – see Figure 5.

In order to exchange these boundary conditions in a proper way, a dynamic communication between the three sub-buildings is required and can be achieved by using EnergyPlus with External Interfaces and especially with the Building Controls Virtual Test Bed (BCVTB) (Wetter, 2011).
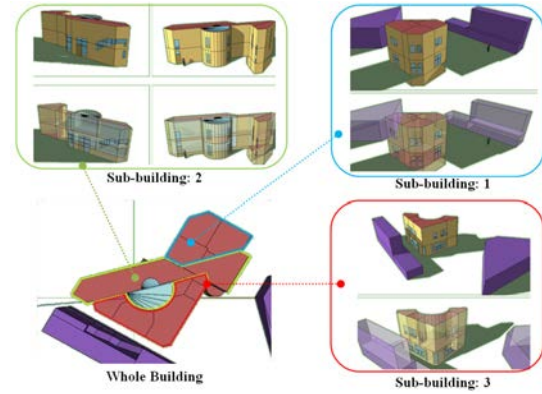

Figure 4: Dividing the whole building to 3 sub-buildings
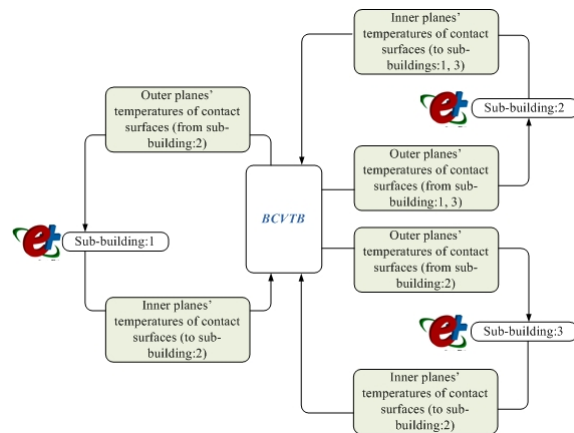

Figure 5: Data exchange between the sub-building through BCVTB

Through such a dynamic communication, a co-simulation between three different thermal models, developed in EnergyPlus, is achieved and the boundary conditions on "boundary walls" (contact surfaces) are defined as follows:

- Suppose that the subscripts x_1 and x_2 and x_3 to denote the state variable of the corresponding sub-building and the function f_1, f_2 and f_3 that computes the next state variable of the simulator 1 and 2 and 3, respectively. The simulator 1 computes, for each time step k, the sequence: $x_1(k + 1) = f_1(x_1(k), x_2(k), x_3(k))$ and similarly, simulators 2 and 3 compute the sequences $x_2(k+1) = f_2(x_1(k), x_2(k), x_3(k))$, $x_3(k + 1) = f_3(x_1(k), x_2(k), x_3(k))$ respectively, with initial conditions $x_1(0) = x_{1,0}$, $x_2(0) = x_{2,0}$ and $x_3(0) = x_{3,0}$.

- The state variable x_1 contains the temperatures of inner planes of all that surfaces which belong to sub-building:1 and which are temperatures of outer planes of the corresponding surfaces which belong to sub-building:2.

- The state variable x_2 contains the temperatures of inner planes of all that surfaces which belong to sub-building:2 and which are temperatures of outer planes of the corresponding sur-

faces which belong to sub-building:1 and sub-building:3.

- The state variable x_3 contains the temperatures of inner planes of all that surfaces which belong to sub-building:3 and which are temperatures of outer planes of the corresponding surfaces which belong to sub-building:2.

- To advance from time k to $k+1$, each simulator uses its own time integration algorithm. At the end of the time step, the simulator 1 sends the new state $x_1(k+1)$ through the BCVTB and receives the state $x_2(k+1)$ through the BCVTB. The same procedure is done with the simulators 2 and 3. The BCVTB synchronizes the data in such a way that it does not matter which of the three simulators is called first.

SIMULATION RESULTS

Towards investigating the accuracy of the simulation results, both the full-scale and reduced (after the implementation of a speedup technique) model are simulated for a predefined time interval (run period), and standard deviation of the difference between the resulting zone air temperatures are calculated according to the following equations.

To start, the temperature difference between the full-scale and the reduced model simulation results is given by:

$$\Delta T_i = T_{\text{full-scale},i} - T_{\text{reduced},i}. \quad (6)$$

Consecutively, the mean is calculated according to:

$$\overline{\Delta T} = \frac{1}{n} \sum_{i=1}^{n} \Delta T_i; \quad (7)$$

while, the standard deviation is calculated as follows:

$$s = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} \left(\Delta T_i - \overline{\Delta T} \right)^2}. \quad (8)$$

The deviation is given as $\overline{\Delta T} \pm s$. A large $\overline{\Delta T}$ points in the direction of a general failure, whereas a large s indicates a high uncertainty for the reproducibility. The reason for a general failure can be either a wrong model or wrong parameterizations.

For the simulation speedup on the other hand, the simulation runtimes for a number of cases, performed to record the reduction in simulation runtime due to the implementation of a speed-up technique, are presented.

FIBP Building

The required simulation time of a *basic* building simulation in TRNSYS scales up with increasing number of thermal zones according to the polygon shown in Figure 6 — the relevant calculation time in *seconds* is on the left axis. The right axis refers to the simulation time in minutes required to simulate the full-scale and

the simplified (tower) FIBP building model. The simulation time of the full-scale model including all thermal zones (25), is approximately 800 minutes for one year. The tower (9 zones) takes approximately 50 minutes for the same simulation interval. Since the models were designed for the purpose of co-simulation the following considerations are relevant.

Co-simulation requires repeated simulations for the prediction horizon in connection with a stochastic optimization algorithm; the number of zones increases the dimension of the parameter space and hence prolongs the convergence time and the number of iterative simulations required by the algorithm. A prediction horizon of 72 hours including a one day settling phase requires approximately 7 minutes simulation time for the full-scale model. Assuming 100 iterations — which is a conservative estimation for a 54 dimensional parameters space — to find an optimum, a controller design would take approximately 11 hours. This allows for only two complete controller design runs a day. Using the tower model requiring only 24 s for the relevant prediction horizon, at least 24 runs per day are possible.
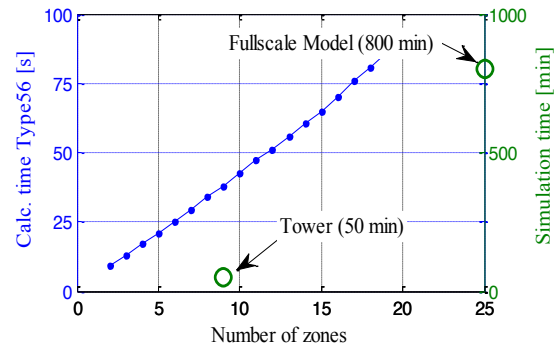

Figure 6: Upscaling of the simulation runtime for increasing number of thermal zones in TRNSYS Type 56 — base interval is one year. Left axis: general building model, right axis: fullscale FIBP & tower building model

In order to compare the impact on the results for this simplification, two simulations for a winter month (January) and two simulations for a summer month (June) are conducted. The setpoint temperatures (blue dashed line) — available from real measurement data — are applied as room set temperatures for the three zones R007, R107 and R207. Figure 8 shows that, for winter months, although a phase shift is clearly visible, temperature patterns are very similar.

However, in summer we have a clear overestimation of the temperatures which is due to the fact, that neighboring rooms receive some sort of cooling e.g. night ventilation, while for the tower zones no window opening or any other user influence was considered. In addition, the summer interval shows the significance of the thermal stratification in vertical direction; the difference between the bottom and the top zone is approximately 5 K.
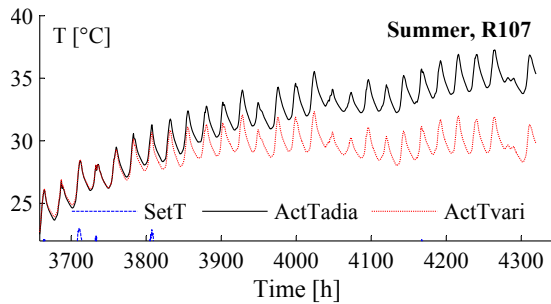
Figure 7: FIBP tower building model – different boundary conditions, for a simulation interval of a summer month
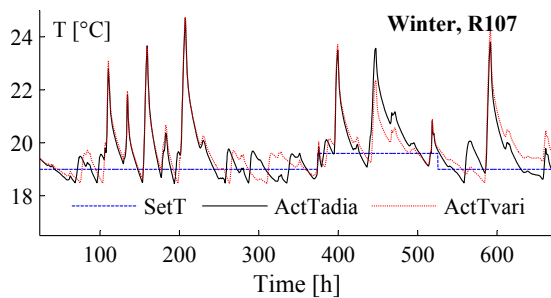

Figure 8: FIBP tower building model – different boundary conditions, for a simulation interval of a winter month

Hence, if rooms are operated similarly as is the case for winter, the two optional boundary condition lead to nearly the same results. But if the neighboring room is operated differently, as is the case for the winter month, the thermal coupling leads to systematic over- or underestimation.

The mean and the standard deviation of the expression $\Delta T_i = \mathrm{ActTvaria}_i - \mathrm{ActTadia}_i$, characterize the similarity of the temperature trajectories for different boundary conditions. Variable boundary conditions ($\mathrm{ActTvaria}_i$) are considered providing the same conditions for the tower as would be prevalent for these zones embedded in the full-scale model. Results of the deviation are presented in Table 1.

Table 1: Mean and standard deviation results for rooms R207, R107 and R007 of the FIBP tower building model

Thermal Zone	Winter month		Summer month	
	$\overline{\Delta T}$	s	$\overline{\Delta T}$	s
R207	-0.020	0.145	-2.14	1.91
R107	0.055	0.476	-2.51	1.92
R007	-0.005	0.527	-1.96	1.40

TUC Building

Moving to the TUC Building simulation experiments setup, a whole year simulation time interval is selected to investigate the deviation, proving that a parallel connection between the sub-buildings is able to assimilate zone air temperature trends of a full-scale

model, regardless of the neighboring zones thermal conditions (temperature, humidity, etc.). Thus, assuming all zones to be free floating, the conditions during this period are as follows: shading devices are completely open; internal gains are equal to zero, since lights and electric equipment are switched off; there is no HVAC system available to control the temperature of the zone; and natural ventilation is considered at night, during summer months only.
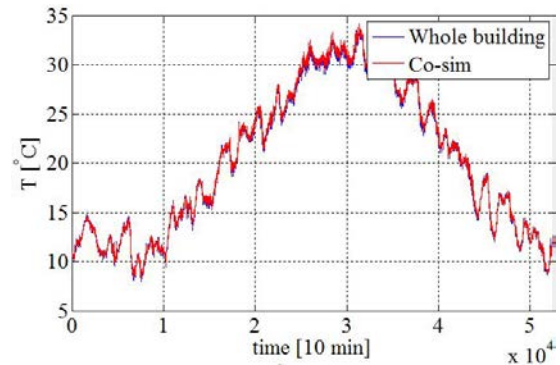

Figure 9: Simulated Air Temperature values in an office room (office 11) — whole building model and sub-building:1 model (Co-sim)

Observing the temperature results in Figure 9, it is obvious the similarity of trends (almost identical) for a randomly selected office room (office 11 – part of sub-building:1). Although the temperature differences are near to zero during the winter months, slight differences, which are within acceptable limtis, arise during the summer months, proving that the above types of boundary conditions are efficient enough to describe the dynamic behavior of the full scale building. The mean and the standard deviation for the office rooms are presented in Table 2.

Table 2: Mean and standard deviation results for each office room of TUC building

Thermal Zone	Whole year	
	$\overline{\Delta T}$	s
office 1	0.168	0.028
office 2	0.238	0.033
office 3	0.153	0.025
office 4	0.251	0.027
office 5	0.132	0.075
office 8	0.251	0.060
office 9	0.225	0.051
office 10	0.251	0.053
office 11	0.251	0.082
office 13	0.173	0.065

Three scenarios are investigated to prove the effectiveness of the parallel connection, regarding the simulation runtime for different run periods. In Table 3, Full is considered to be the full-scale TUC Building model, Sub:1, Sub:2 and Sub:3 are the simulation models of the sub-buildings presented in Figure 4, runing in-

dependently with boundary conditions described by Equation 5 and coefficients $c_1 = 0.5, c_2 = 0.5, c_3 = c_4 = c_5 = 0$; and Co-sim describes the parallel simulation which was presented above.

While one might expect expect that the the runtime of the parallel simulation should coincide with the maximum value comparing Sub:1, Sub:2 and Sub:3 simulation runtimes at each run period (one day, one week and one month), Table 3 shows that, when the run period of simulation is growing, the resulting runtime of the dynamic connection is always greater than the corresponding runtime of sub-buildings. This is due to the large size of data exchanged through the co-simulation.

Table 3: Simulation runtimes for each sub-building (Sub:1, Sub:2 and Sub:3), the parallel simulation (Co-sim) and the whole building (Full)

Run Period	sub:1 (sec)	sub:2 (sec)	sub:3 (sec)	Co-sim (sec)	Full (sec)
1 day	13.6	9.9	13.2	15.4	98.9
1 week	20.5	21.9	17.3	37.8	201.1
1 month	47.4	75.5	33.5	120.9	612.9

Nevertheless, it is estimated that, dividing the whole building to three sub-buildings leads to a reduction of simulation runtime by 80%. Such a result was expected since the division of the original building has significantly reduced the number of thermal zones, walls and windows, as shown in Table 4.

Table 4: Number of zones, walls and windows for each sub-building (Sub:1, Sub:2 and Sub:3) and the whole building (Full-scale)

Model	Full-scale	Sub:1	Sub:2	Sub:3
Zones	30	8	14	8
Walls	281	101	107	99
Windows	105	33	51	21

CONCLUSION

In the present work, two techniques aiming at reducing the computational cost of zonal-type building simulation models are presented: (i) geometry simplification for periodic geometries; and, (ii) the use of co-simulation to split a building into simpler sub-buildings, that can be evaluated in parallel and exchange boundary conditions data at each simulation timestep. These simulation speed-up approaches are evaluated, with respect to accuracy and computational effort, in two real demonstration buildings. Regarding the computational effort, the efficiency of both techniques is supported by the results, which at the same time highlight the necessity of elaborate boundary conditions definition, since experiments show that unrealistic boundary conditions can lead to substantial over- or under-estimation of zone air temperature.

Geometry simplification experiment shows that even though, a significant simulation runtime speed-up is achieved, the inability to provide efficient boundary conditions, affects its efficiency. Co-simulation approach on the other hand, yields an effective method since, as the present work shows, its implementation leads to a reduction of the simulation runtime up to 80% and at the same time manages to accurately define the boundary conditions between the sub-buildings.

ACKNOWLEDGEMENT

Nomenclature

$\mathbf{n}$	vertical vector
∇T	temperature gradient
q_{c_i}	convective heat transfer to the zone air
q_{c_o}	convective heat transfer to the outside air
q_{k_i}	conduction heat transfer through the wall
q_{k_o}	conduction heat transfer into the wall
q_{lw_i}	longwave radiant exchange transfer between zone surfaces and longwave radiation transfer from equipment in zone
q_{lw_o}	longwave radiant exchange with the air and surroundings
q_{sol_i}	transmitted solar radiation flux absorbed at surface
q_{sol_o}	absorbed solar shortwave radiation flux
q_{sw_i}	shortwave radiation transfer to surface from lights
T_g	ground temperature
T_{sch}	temperature schedule for the outer plane of the surface
T_{so}	outer plane surface temperature - boundary condition
v_w	outdoor wind speed

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