# Comparison of co-simulation approaches for building and HVAC/R system simulation

Document status and date:
Published: 01/01/2007

Document Version:
Accepted manuscript including changes made at the peer-review stage

Please check the document version of this publication:

• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
• The final author version and the galley proof are versions of the publication after peer review.
• The final published version features the final layout of the paper including the volume, issue and page numbers.

Link to publication

Download date: 04. Oct. 2023

# COMPARISON OF CO-SIMULATION APPROACHES FOR BUILDING AND HVAC/R SYSTEM SIMULATION

Marija Trcka[1*] , Michael Wetter[2*], and Jan Hensen[1]

[1]Technische Universiteit Eindhoven, Eindhoven, The Netherlands,
[2]Simulation Research Group, Building Technologies Department, Environmental Energy
Technologies Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720
Contact e-mail: m.trcka@tue.nl

## ABSTRACT

Appraisal of modern performance-based energy codes, as well as heating, ventilation, air-conditioning and refrigeration (HVAC/R) system design require use of an integrated building and system performance simulation program. However, the required scope of the modeling library of such integrated tools often goes beyond those offered in available simulation programs.

One remedy for this situation would be to develop the required models in an existing simulation program. However, due to the lack of model interoperability, the model would not be available in other simulation programs.

We suggest co-simulation for HVAC/R system simulation as an approach to alleviate the above issues. In co-simulation, each subsystem is modeled and simulated in the appropriate simulation program, potentially on different computers, and intermediate results are communicated over the network during execution time.

We discuss different co-simulation approaches and give insights into specific prototypes. Based on the prototypes, we compare the approaches in terms of accuracy, stability and execution time, using a simple case study. We finish with results discussions and recommendations on how to perform co-simulation to maintain the required accuracy of simulation results.

## KEYWORDS

Co-simulation, External coupling, Run-time operability, Integrated building performance simulation.

## INTRODUCTION

The scope of relevant aspects for different building systems design analysis is extensive as it includes building envelope, air and hydronic distribution systems, different-source heat gains, controls, different HVAC/R systems, and combined cooling, heating and power systems. For analyzing building systems, an integrated simulation approach is required as these subsystems interact with each other. However, available tools in the domain of building performance are not equally suited for modeling and simulation of all relevant aspects and for all possible design analysis. For example, some tools are better suited for building envelope simulation (e.g. EnergyPlus, ESP-r), some for HVAC system simulation (e.g. Modelica, TRNSYS) and others for refrigeration systems (e.g. DOE-2.2 refrigeration version 49a). Previously (Hensen 1991, Hensen and Clark 2000), it has been argued that building system modeling and simulation capabilities develop slowly and take up an enormous amount of resources (time wise and financial). Run-time interoperability allows taking advantage of these developments that occur in different tools, as opposed to being restricted with the capabilities of one particular program. This run-time interoperability can be achieved by co-simulation. By co-simulation, we mean a particular case of simulation scenario where two solvers, which originate in different simulators, running simultaneously and exchanging relevant coupling data at the synchronization time points, solve a coupled system of equations (Figure 1).
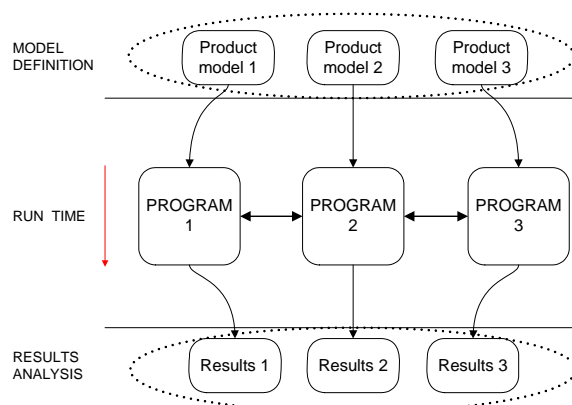


*Figure 1: Data flow in co-simulation*

A review of research and developments in co-simulation in BPS as well as other fields is given elsewhere (Trcka {Radosevic} et al. 2006b). Also related to our work is the research in partitioned

---

solution for fluid-soil interaction analysis (Park 1980 and Piperno 1997), partitioned solution for simulating water flow in a variably saturated dual-porosity medium Tseng (1997) and partitioned simulation algorithms for simulation of multi-body dynamics (Arnold 2004).

In this paper we discuss different co-simulation implementation strategies for HVAC/R systems. Co-simulation of building and HVAC/R systems performance tools, as well as domain independent tools, enables combining component and system models that are available in different simulation programs. For example, a building can be modeled in different domain simulation tools, such as ESP-r and EnergyPlus, taking advantage of the latest developments on the building side. A coupled HVAC/R system can be modeled in one of the drag-and-drop environments, such as TRNSYS or Modelica, making the overall modeling process easier and faster, and exploiting the application of advanced controllers and innovative building components and systems that are difficult or not feasible to model in the previously mentioned tools.

We will show that the run-time communication between the legacy simulation programs enables a modeler to model across various environments, while exploiting advances of each.

## CO-SIMULATION IMPLEMENTATION

This section of the paper addresses relevant issues regarding different co-simulation prototypes that we implemented and it discusses the prototypes in more detail.

### Inter process communication (IPC) and synchronization

Different IPC mechanisms were used in the course of the co-simulation development. For the results reported in this paper, coupled programs exchange data through a shared memory buffer. For this purpose the free Fortran library *ShareBufferWin32* is used. A portion of the shared buffer is reserved for IPC control and synchronization. Boolean values indicate the availability of new coupling data for communication in both directions. For synchronization, a process that requires a new value will wait until the value becomes available.

### System decomposition

We implemented two different system-decomposition implementations. We call the first implementation *intra-domain* decomposition. It requires that HVAC/R component models are used in both coupled programs. The name reflects that the system is decomposed inside the HVAC/R domain only. The decomposition is done by virtually cutting pipes and ducts. The coupling data are based on the properties of the working fluid passing through these connecting pipes and ducts. In addition to a working fluid state (at the sending nodes) and transport variables, for the distributed control purpose sometimes there is a need to transfer state variables from a remote node in the system. So far, the components enable transfer of any zone air temperature and humidity ratio.

We call the second implementation *inter-domain* decomposition. In inter-domain decomposition, a system can be decomposed between the building and the HVAC/R system domain. Subsystems may constitute of only building or only HVAC/R system components. Consequently, the exchange of heat rate and moisture flow rate in one, and temperature (and heat transfer coefficient) and humidity ratio in another direction is required. Inter-domain decomposition allows for example for a supermarket to simultaneously simulate in TRNSYS the refrigerated cases and the HVAC/R system and in EnergyPlus the building heat transfer. To implement this approach, we had to make additional changes to the code of TRNSYS 16 and EnergyPlus v.1.2.2, as we will describe below.

### Coupling strategies

There are two different co-simulation coupling strategies:

- *Quasi-dynamic coupling* (Zhai 2003), also called *loose coupling* (Struler et al. 2000), or *ping-pong coupling* (Hensen 1999), where distributed models run in sequence, and one model uses the known output values, based on the values at the previous time steps, of the coupled model. The feedback between the programs is lagged one coupling time step.

- *Fully-dynamic coupling* (Zhai 2003), also called *strong coupling* (Struler al. 2000), or *onion coupling* (Hensen 1999), where distributed models iterate within each time step until the error estimate falls within a predefined tolerance.

### Used software

Early co-simulation prototypes have been developed using TRNSYS 16, EnergyPlus (v1.2.2) and ESP-r (10.6), see Trcka {Radosevic} et al. (2006a). The code of each tool has been modified to enable run-time communication with other executables.

For the results reported in this paper, the above described co-simulation approaches (implementing different system decomposition points and different coupling strategies) were prototyped using EnergyPlus and TRNSYS.

EnergyPlus has a good envelope model, but system modeling can be cumbersome due to the lack of a drag and drop graphical user interface. At the same

time, the modeling flexibility of system control is limited to set point managers.

The solution algorithm in EnergyPlus constitutes of basically three steps: 1) prediction, 2) HVAC system simulation, and 3) correction. Prior to the prediction step, the terms that define gains/losses through the building envelope, internal heat gain, infiltration loads and loads due to the air exchange with other zones are established. Then, based on the set point temperature and/or humidity ratio, the required load by the system is estimated. Based on the required load, the system components are simulated using a solution inverter that calculates the required input based on the requested output[†]. The required input is then sent upstream as required outputs of the upstream components. An iterative procedure is employed to take into account that not all components may be able to provide the required output (such as due to a limited cooling capacity). The third step is a correction of the zone temperature, based on the actual calculated system output. Since the time constants of the HVAC system and the zone air are typically much smaller than those of the building structure, EnergyPlus employs a variable time step for the zone air and the HVAC system. The time step is controlled based on the change in zone temperature per time step. The required system time step is not predetermined, but rather calculated during the simulation. Since most the building performance simulation (BPS) tools cannot adjust their time step during run-time to an adaptive value that is prescribed by an external signal, we have set the EnergyPlus system time step to a fixed, user-specified value. The minimum value of the user specified time step is set to 1 minute.

In order to use some zone equipment from EnergyPlus (intra-domain system decomposition), several tricks had to be made. For example, we wanted in TRNSYS to simulate a hydronic system that supplies a radiator modeled in EnergyPlus. The system adjusts the water flow rate to meet the zone heating requirements (the zone is also modeled in EnergyPlus). To achieve this, we had in EnergyPlus to disable the local ideal control. If we had specified in EnergyPlus that the zone is uncontrolled, then the radiator component would not have been called, as the EnergyPlus predictor estimates that there is no need for system operation. The set points, therefore, needed to be specified in the way to allow the component to be manipulated by TRNSYS.

TRNSYS, has an extensive library of HVAC/R components. However, the building model is not as extensive as the building model in EnergyPlus.

TRNSYS makes a distinction between components whose output is time-dependent and between components whose output depends only on its input and not explicitly upon time. TRNSYS also has special components that are called after all other components have converged. The information that indicates the component type is stored in an array and determines the calling sequence of the component during the iteration. We used this array to control when the components that we developed for co-simulation are called. The components that read the data from EnergyPlus are executed only in the first iteration of each time step, while the components that communicate the converged solution to EnergyPlus are called when all other components have converged.

## Prototypes

For the same simulation time step, the loose coupling approach significantly decreases the computation time, but it might not be as accurate as the strong coupling approach. The Figure 2 shows the flow-chart for the loose coupling.
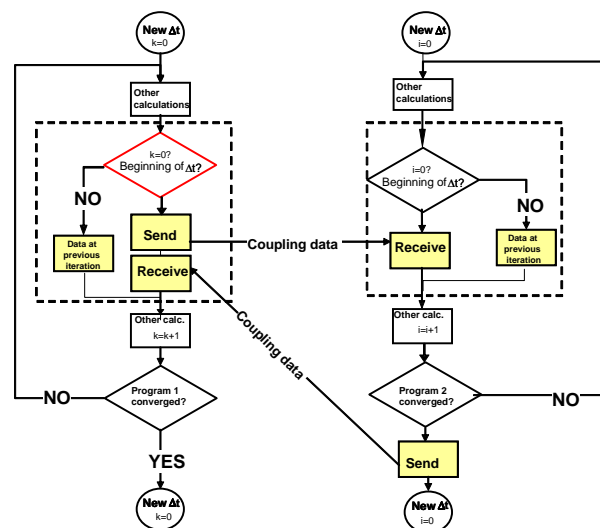


*Figure 2: Flow-chart of loosely-coupled implementation. In our prototype, EnergyPlus takes the role of the program whose information flow is represented on the left side of the figure. The information flow of the second program corresponds to the TRNSYS role.*

In the first iteration step during the current time step (if *i=0* for TRNSYS or *k=0* for EnergyPlus), the programs communicate the coupling data. EnergyPlus sends the known (from a previous time step) coupling data to TRNSYS. Based on that data, TRNSYS performs the full time step simulation until all

---

† EnergyPlus in general uses ideal control of system components in order to maintain a specified set point(s) at their outlets. The set point(s) at the outlet of a component can be calculated by set point managers based on the data at the remote nodes.

$$T_z^t = \frac{\sum_{i=1}^{N_{HGS}} \dot{Q}_i + \sum_{i=1}^{N_{surfaces}} h_i A_i T_{si} + \sum_{i=1}^{N_{zones}} \dot{m}_i c_p T_{zi} + \dot{m}_{inf} c_p T_\infty + \dot{m}_{sys} c_p T_{sup\,ply} - \frac{C_z}{\Delta t}\left(-3T_z^{\,t-\Delta t} + \frac{3}{2}T_z^{\,t-2\Delta t} - \frac{1}{3}T_z^{\,t-3\Delta t}\right)}{\frac{11}{6}\frac{C_z}{\Delta t} + \sum_{i=1}^{N_{surfaces}} h_i A_i + \sum_{i=1}^{N_{zones}} \dot{m}_i c_p + \dot{m}_{inf} c_p + \dot{m}_{sys} c_p} \tag{1}$$

$$T_z^t = \frac{\sum_{i=1}^{N_{CIL}} \dot{Q}_i + \sum_{i=1}^{N_{surfaces}} h_i A_i T_{si} + \sum_{i=1}^{N_{zones}} \dot{m}_i c_p T_{zi} + \dot{m}_{inf} c_p T_\infty + \dot{m}_{sys} c_p T_{sup\,ply} + (\dot{m}_{sys} c_p)_{TRNSYS} T_z^{\,t-\Delta t} - \frac{C_z}{\Delta t}\left(-3T_z^{\,t-\Delta t} + \frac{3}{2}T_z^{\,t-2\Delta t} - \frac{1}{3}T_z^{\,t-3\Delta t}\right)}{\frac{11}{6}\frac{C_z}{\Delta t} + \sum_{i=1}^{N_{surfaces}} h_i A_i + \sum_{i=1}^{N_{zones}} \dot{m}_i c_p + \dot{m}_{inf} c_p + \dot{m}_{sys} c_p + (\dot{m}_{sys} c_p)_{TRNSYS}} \tag{2}$$

components have converged. Then, TRNSYS sends the converged coupling data to EnergyPlus. Next, based on the received data EnergyPlus performs its time step simulation involving iterations during which the data that have been received from TRNSYS are held constant.

To understand how the data communicated from TRNSYS are incorporated in EnergyPlus' zone temperature correction formula, we state in (1) the energy balance equation in the form used by EnergyPlus in the third step of its solution process, i.e., the correction step. In intra-domain decomposition, we implemented the coupling using the term $\dot{m}_{sys} c_p T_{sup\,ply}$ in (1). In inter-domain decomposition, we implemented the coupling using the term $\sum_{i=1}^{N_{HGS}} \dot{Q}_i$ in (1). In inter-domain decomposition, the coupling heat rate is calculated based on the zone temperature from the previous time step which makes the zone temperature an explicit variable in (1). However there are means to improve the accuracy by correcting the equation for the lagging, which we will now present.

The heat rate for the intra-domain decomposition is: $\dot{Q}_{sysTRNSYS,intra\text{-}dec} = \dot{m}_{sys}^t c_p^t (T_{supply}^t - T_z^t)$, while it is for the inter-domain decomposition: $\dot{Q}_{sysTRNSYS,inter\text{-}dec} = \dot{m}_{sys}^t c_p^t (T_{supply}^t - T_z^{\,t-\Delta t})$. To obtain the intra-domain from inter-domain form, we are adding a correction term to the energy balance equation to correct for the lagging of the zone temperature. With correction terms, we can write $\dot{Q}_{sysTRNSYS,inter\text{-}dec} + \dot{m}_{sys}^t c_p^t (T_z^{\,t-\Delta t} - T_z^t) = \dot{Q}_{sysTRNSYS,intra\text{-}dec}$ and include this in the heat balance equation. The value of $\dot{m}_{sys}^t c_p^t$ is provided by TRNSYS. A similar equation applies if the heat exchange between the system and the zone is in the form $(UA)_{sys}^t (T_{sys}^t - T_z^{\,t-\Delta t})$.

Applying the correction term to the energy balance equation, we obtain (2). We use (2) to update EnergyPlus' zone air temperature for inter-domain system decomposition.

Strong coupling allows longer time steps than quasi-dynamic coupling for the same accuracy. In strong coupling, coupled programs iterate within one time step, as explained earlier. The iteration process is criterion is based on the difference between two subsequent received values of coupling data from TRNSYS. If the difference is greater than a specified value, EnergyPlus will request another iteration.
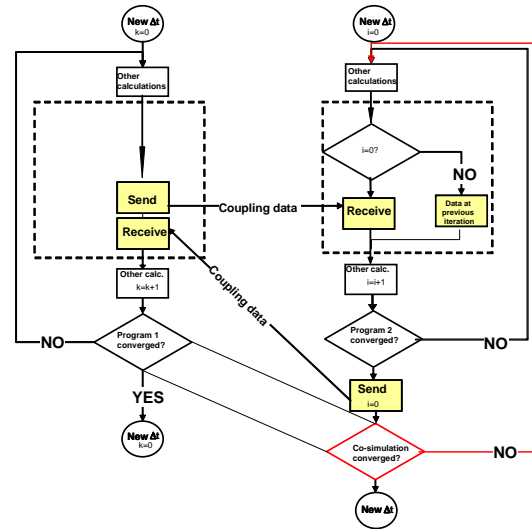


*Figure 3: Flow-chart of strongly-coupled implementation. In our prototype, EnergyPlus takes the role of the program which information flow is represented on the left side of the figure. The information flow of the second program corresponds to the TRNSYS role.*

Let $k = \{0, 1, 2, .., N_{max}\}$ denote the iteration counter of the EnergyPlus solver, which maximum value is limited by $N_{max}$. Equation (3) shows the EnergyPlus integration step for co-simulation using strong coupling strategy. In inter-domain decomposition, the internal heat gain $\sum_{i=1}^{N_{HGS}} \dot{Q}_{i,k}$ contains the system heat rate calculated in TRNSYS in *k-th* iteration. In intra-domain decomposition, internal gains remain unchanged in subsequent iterations, while the coupling to TRNSYS is implemented using $\dot{m}_{sys,k}^t c_p^t T_{supply,k}^t$.

If the system in TRNSYS is oversized, controllers are not tuned correctly or the simulation employs large time steps, a small change in the sensed variable can generate a large change in system output,

leading to non-convergence of the coupled system of equations. To alleviate this problem, we relax the sensed

$$T_{z,k+1}^t = \cfrac{\displaystyle\sum_{i=1}^{N_{HGS}} \dot{Q}_{i,k} + \sum_{i=1}^{N_{surfaces}} h_i A_i T_{si} + \sum_{i=1}^{N_{zones}} \dot{m}_i c_p T_{zi} + \dot{m}_{\inf} c_p T_\infty + \dot{m}_{sys,k} c_p T_{\sup ply,k} - \dfrac{C_z}{\Delta t}\left(-3T_z^{t-\Delta t} + \dfrac{3}{2}T_z^{t-2\Delta t} - \dfrac{1}{3}T_z^{t-3\Delta t}\right)}{\dfrac{11}{6}\dfrac{C_z}{\Delta t} + \displaystyle\sum_{i=1}^{N_{surfaces}} h_i A_i + \sum_{i=1}^{N_{zones}} \dot{m}_i c_p + \dot{m}_{\inf} c_p + \dot{m}_{sys,k} c_p} \qquad (3)$$

variable (the zone temperature in our case) using $T_{z,k+1\,relaxed}^t = 0.25 T_{z,k+1\,non-relaxed}^t + 0.75 T_{z,k}^t$. Using a large coefficient for $T_{z,k}^t$ resulted in faster convergence.

## CASE STUDY

We built a one-zone model in EnergyPlus and an air system model in TRNSYS and coupled them through co-simulation.

**Description of the physical system**

The system consists of a cooling coil, which we sized to fit the zone load, a constant flow fan and a variable flow cooling water pump. The water mass flow rate was proportionally controlled to maintain the zone temperature set point, with a lower limit of 24°C and an upper limit of 26°C. The inlet cooling water temperature was kept constant at 6°C. The system was operating from 7am to 7pm.

The nominal value of the water flow rate was varied from 720 kg/h to 1800 kg/h. The first nominal value corresponds to the maximal cooling demand for the simulated period, the second value was used to demonstrate the effect of an oversized system on stability of the co-simulation.

**Description of the simulation models**

There are two different models in EnergyPlus. For inter-domain decomposition, the EnergyPlus model consists only of the building model. For intra-domain decomposition, the EnergyPlus model includes ducting from the zone to the cooling coil modeled in TRNSYS and from the cooling coil the zone.

We used the weather data for Denver, Colorado. The simulation period was two working days from the 1st to the 2nd of August.

**Results**

We used different building and HVAC/R co-simulation approaches and compared the zone temperature and cooling water flow rate.

For the first comparison we used a time step of 1 min. Figures 4 and 5 show that the zone temperature and cooling water flow rate obtained with all four combinations of system decompositions and coupling strategies are almost identical.

There is a small difference in cooling water flow rate between loosely-coupled and strongly-coupled cases, which can be seen from the magnified view of

the graph shown in Figure 6. In loosely coupled co-simulation, the oscillations of the water flow rate occur due to the use of the lagged coupling data.
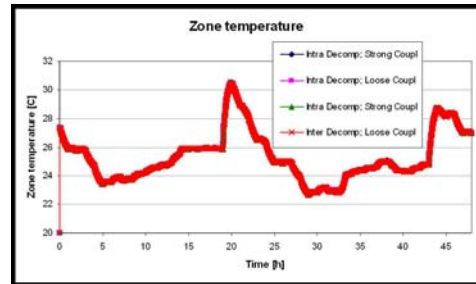


*Figure 4: Zone temperature, for a time step of 1 min and nominal cooling water flow rate – 720 kg/h; for all co-simulation approaches*
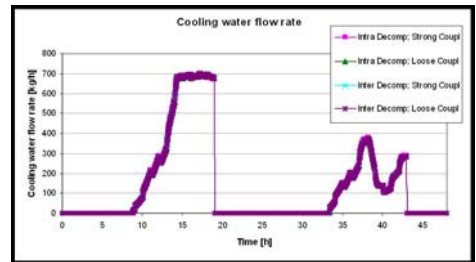


*Figure 5: Cooling water flow rate, for time step of 1 min, and nominal cooling water flow rate – 720 kg/h; for all co-simulation approaches*
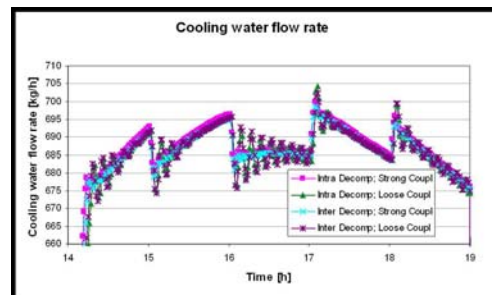


*Figure 6: Magnified view: Cooling water flow rate, for time step of 1 min, and nominal cooling water flow rate – 720 kg/h; for all co-simulation approaches*

For strongly coupled co-simulation, we encountered convergence problems for larger time steps. The number of iterations reached the maximum number

allowed per time step ($N_{max}$), which we set at 20, at almost every simulation time step. This is why we implemented the relaxation of the zone temperature. Due to the adequately sized system, the difference between the loose and strong coupling is small in this case ($\Delta t$=10min), as shown on Figures 7 and 8, although bigger than in the previous case ($\Delta t$=1min). The oscillations are within $\pm 0.3^{o}$C and $\pm 100$kg/h.

The biggest oscillations were observed for co-simulation that uses loose coupling. The phase difference between inter- and intra-domain system decomposition is due to the exchanges of differently updated coupling data. When using inter-domain system decomposition, EnergyPlus sends the updated zone temperature, while in intra-domain system decomposition, the temperature of the inlet node that is not yet updated is sent to TRNSYS.
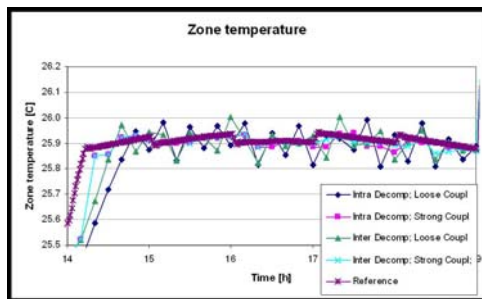


Figure 7: Magnified view: zone temperature, for time step of 10 min, and nominal cooling water flow rate – 720 kg/h; for all co-simulation approaches and relative to the reference curve obtained by co-simulation using a time step of 1min
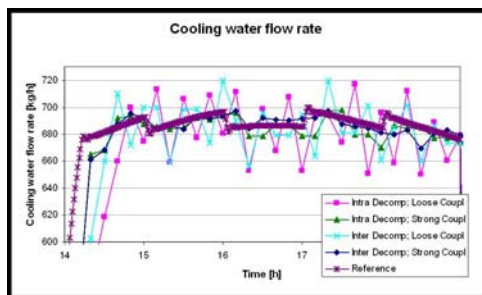


Figure 8: Magnified view cooling water flow rate, for time step of 10 min, and nominal cooling water flow rate – 720 kg/h; for all co-simulation approaches and relative to the reference curve obtained by co-simulation using a time step of 1min

In strongly coupled co-simulation, good performance was achieved with relaxation even in the case with higher nominal cooling water flow rate and bigger time step. Figure 9 shows how the results from loosely coupled co-simulation correspond to strongly coupled co-simulation results using relaxation of zone temperature for $\Delta t$=30min and nominal mass flow rate of cooling water 1800 kg/h, for intra-

domain decomposition. The solution of strongly coupled co-simulation with relaxation follows the reference curve (obtained using $\Delta t$=1 min) more closely than the solution obtained by loosely coupled co-simulation using the same time step.
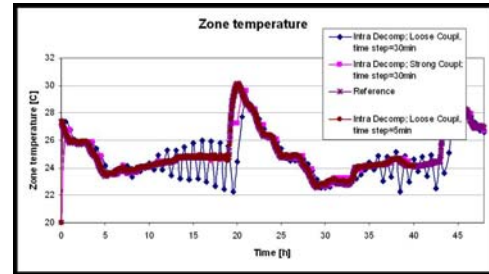


Figure 9: Zone temperature, for nominal cooling water flow rate – 1800 kg/h; for intra-domain system decomposition, using loose (for time step of 5 and 30min) and strong (with relaxation) ( for time step of 30min) coupling strategies and relative to the reference curve obtained by co-simulation using a time step of 1min.
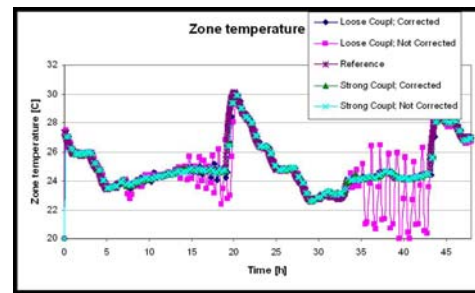


Figure 10: Zone temperature, for time step of 15 min, and nominal cooling water flow rate – 1800 kg/h; for inter-domain system decomposition, using loose and strong (with relaxation) coupling strategies, with and without correction for lagging of data sent from EnergyPlus to TRNSYS and relative to the reference curve obtained by co-simulation using a time step of 1min

Above, EnergyPlus obtained $\dot{m}_{sys}c_p$ from TRNSYS, which allowed us to use the corrected version of the zone temperature update as shown in (2). For loose-coupling, the correction significantly affects the results as shown in Figure 10. In Figure 10, the results were obtained with a coupling time step of 15 min. If a shorter time step were used, the difference between corrected and not corrected results would be smaller.

We also investigated the use of a first-order predictor, as we will now discuss. In the above simulations, TRNSYS performed its calculations based on the one-time-step delayed coupling data. For small coupling time steps, the introduced numerical error was negligible, but the error was larger for large

coupling time steps. To improve the accuracy of the loosely coupled co-simulation, we implemented a first-order predictor that predicts future coupling data sent from EnergyPlus to TRNSYS. The predictor increased the accuracy in situations where the variations in the changes of input data from one time step to another were small relative to the subsystem's time constant, provided that the coupling time step was in the order of the subsystem's time constant. However, in more realistic settings where the changes of an input were not smooth, and the time step was large relative to the subsystem time constant, the predictor overestimates the future value of the coupling data. This led to additional inaccuracies, as shown in Figure 11. Hence, using a first order predictor is not recommended for simulations.
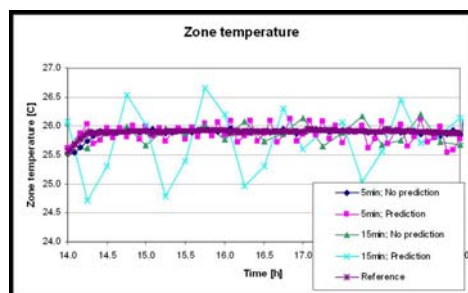


*Figure 11: Magnified results: zone temperature, for time step of 5 min and 15 min, and nominal cooling water flow rate –1800 kg/h; for inter- domain system decomposition, using loose and strong coupling strategies, with and without prediction of coupling data sent from EnergyPlus to TRNSYS and relative to the reference curve obtained by co-simulation using time step of 1min*

The computation time differs a lot from one approach to another. The longest execution time was required by intra-domain decomposition with strong coupling. This approach solves the HVAC system in EnergyPlus and practically uses the biggest number of iterations per time steps, as it involves three nested iteration loops[‡]. The second slowest approach was inter-domain decomposition with strong coupling, which does not require the solution of the HVAC system in EnergyPlus, but only in TRNSYS, and has one nested iteration loop less than the previous approach.

The difference in execution time between two loosely coupled approaches was small. The shortest execution time was obtained for inter-domain decomposition using loose coupling, as it does not solve the HVAC system in EnergyPlus.

---

[‡] The second step in EnergyPlus' solution procedure involves an additional iteration loop which is not shown in Figure 3.

For the case study presented in this paper, the wall-clock time required for the execution of co-simulation of two days simulation time, using intra-domain decomposition with strong coupling and a simulation time step of 30 min was 13 seconds. This is much longer than the 7 second wall-clock time required for co-simulation using intra-domain decomposition with loose coupling and a simulation time step of 5 min. The use of loose coupling with shorter time steps also provided a higher accuracy, as shown in Figure 9. The co-simulations were run on Windows XP, using one CPU with 2.8GHz and 3.25GB RAM.

In summary, the shortest execution time was for loosely coupled co-simulation, but the accuracy will be degraded with increase of the time step. Using strong coupling with relaxation, stable and accurate results were achieved even at greater time steps.

Loose coupling allows the use of multiple time steps in co-simulation, meaning that simulators can run using different simulation time steps. Because of the need for rewinding integrators and time, strong coupling strategy can be used with the here discussed BPS tools only if coupled simulators use equal simulation time steps.

## CONCLUSION

We showed how two legacy BPS tools can be linked for co-simulation. We discussed different co-simulation implementations, and compared their solutions in a case study.

Loose coupling leads to shorter execution time than strong coupling, but strong coupling provides higher accuracy if the coupling time step is large.

We showed that the convergence of the inter-program iteration procedure can be enhanced by introducing relaxation of the sensed variable. The results obtained from the test cases show that relaxation allows using a much larger time step, even for oversized systems.

The use of a corrector to correct for the time lagging of the zone temperature that is used for the heat rate calculation in inter-domain decomposition showed good results. The results obtained from the test cases show that using a corrector allows much larger time steps for loosely coupled co-simulation. Using the non-corrected form of the equation caused numerical instabilities as the simulation time step was increased.

The use of a first-order predictor did not provide better solutions in realistic settings and is not recommended.

Ideally, the system should be decomposed in different domains. The lagging of coupling data for the heat rate calculation should be corrected to avoid numerical instabilities in co-simulation which appear

even at shorter time steps (e.g. instabilities are greatly noticeable at Δt=10min in the example used in this paper).

## ACKNOWLEDGMENTS

## REFERENCES

Arnold M. 2004. "Simulation algorithms in vehicle dynamics" submitted for publication, accessed at: http://www.mathematik.uni-halle.de/reports/sources/2004/04-27report.pdf, Feb. 2007.

Hensen J.L.M. 1991. "On the thermal interaction of building structure and heating and ventilating system", PhD thesis, Eindhoven University of Technology.

Hensen J.L.M. 1999. "A comparison of coupled and de-coupled solutions for temperature and air flow in a building", in ASHRAE Transactions vol. 105:2, pp. 962-969.

Hensen J.L.M. and Clarke J.A. 2000. "Building systems and indoor environment: simulation for design decision support", Proceedings of Architecture (International Conference on Design and Decision Support Systems in Architecture & Urban Planning), Eindhoven University of Technology, pp 177-189.

Park, K.C. 1980. "Partitioned transient analysis procedures for coupled-field problems: Stability analysis", Journal of Applied Mechanics, vol: 47, pp. 370-376.

Piperno, S. "Explicit/implicit fluid/structure staggered procedures with a structural predictor and fluid subcycling for 2D inviscid aeroelastic simulations", International journal for numerical methods in fluids, vol 25, pp. 1207-1226.

Struler, E. de, Hoefliger, J., Kale, L.V., and Bhandarkar, M. 2000. "A new approach to software integration frameworks for multi-physics simulation codes", Proceedings of IFIP TC2/WG2.5, Working Conference on Architecture of Scientific Software, pp. 87-104. Ottawa, Canada.

Trcka (Radosevic), M., Hensen J.L.M., Wijsman, A.J.Th.M. 2006a. "Distributed building performance simulation - a novel approach to overcome legacy code limitations", ASHRAE HVAC&R Research Journal, vol. 12:3a, pp. 621-640.

Trcka (Radosevic), M., Hensen J.L.M., 2006b. "Distributed simulation of building systems for legacy software reuse", Proceedings of 6th International Postgraduate Research Conference, International Built & Human Environment Research Week, pp. 442-454.

Tseng, P.H., Sciortino, A., and van Genuchten, M.Th. 1995. "A partitioned solution procedure for simulating water flow in a variably saturated dual-porosity medium", Advances in Water Resources, vol: 18:6, pp. 335-343.

Zhai Z. 2004. "Developing an Integrated Building Design Tool by Coupling Building Energy Simulation and Computational Fluid Dynamics Program", PhD thesis, Massachusetts Institute of Technology.

## NOMENCLATURE

| | |
|---|---|
| $c_p$ | Specific heat capacity of air |
| $C_z$ | Heat capacity of zone air |
| $i$ , $k$ | Counter |
| $hA$ | Product of convective heat transfer and wall surface area |
| $\dot{m}$ | Air mass flow rate |
| $\dot{m}_{\text{inf}}$ | Infiltration air mass flow rate |
| $\dot{m}_{sys}$ | Air mass flow rate from a system serving the zone |
| $N_{surfaces}$ | Number of surrounding surfaces in the zone |
| $N_{zones}$ | Number of zones from which there is an air flow to the current zone |
| $N_{HGS}$ | Number of different internal heat gain sources |
| $\dot{Q}$ | Internal heat gain from different sources |
| $\Delta t$ | Simulation time step |
| $t$ | Simulation time |
| $T_\infty$ | Ambient temperature |
| $T_s$ | Surface temperature |
| $T_{\text{sup}\,ply}$ | Supply temperature |
| $T_z$ | Zone temperature |