Urban and building multiscale co-simulation: case study implementations on two university campuses

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July 5, 2017

Dear Dr. Beausoleil-Morrison and Dr. Hensen:

July 5, 2017

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Ian Beausoleil-Morrison
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Co-Editors
Journal of Building Performance Simulation

Please find our responses to the follow-up comments made by on of the referees. Overall, we believe that we have fully addressed each issue individually in a way that satisfies the requirements of the journal review process.

Please contact me with any further comments or concerns regarding this resubmission.

Kind Regards,

Dr. Clayton Miller

Review Comment Responses to Journal of Building Performance Simulation Second Submission

Paper Title: Urban and building multiscale co-simulation: case study implementations on two university campuses

July 5, 2017

1 Review Comments

a) p. 13, line 69. we week to co-simulate is incorrect. Please consider we co-simulate.

Fixed – thanks for catching that!

b) p. 12, lines 90-93. The correction the authors made in response to a reviewer comment needs further modification. My comment was Please note that Bueno et al. 2013 generated urban weather with a nodal model and did not directly couple EnergyPlus to a nodal representation of the urban canopy layer. The accuracy of this approach depends on how faithfully users and the model represent the buildings that will later be simulated in detail in EnergyPlus with the modified weather file. This applies to Bueno et al. 2013 and NOT Bueno et al. 2011, in which TEB and EnergyPlus are coupled. In short, one of Buenos papers employed coupling and the other did not; the authors should distinguish them or refer to the single method of their choice.

Very good point - apologies for misunderstanding that point. The Bueno 2013 paper has been removed as it does not utilize coupling.

c) p. 14, line 149. Please delete the redundant per hour after timesteps.

Fixed.

d) P. 15, lines 176-177. In two places, the l in long-wave should be capitalized.

Good catch - good example of why "find and replace" needs to be performed before final proofreading.

e) P. 16, line 189. Please hyphenate urban scale.

This instance has been hyphenated as well as several others in the manuscript

f) p. 17, line 217. Please replace simulation results of the co-simulation with results of the co-simulation.

Fixed.

g) p. 18, line 221. Please replace actualized with actual. In line 224, please replace measured and simulated with measurement and simulation.

Fixed.

h) p. 20, line 283. Please replace co- simulation with co-simulation by removing the extraneous space after the hyphen.

Fixed.

i) p. 21, Figures 10 and 11. The authors have usefully improved these figures. Is it necessary to retain the absolute change in energy consumption, to four significant figures, as well as the percentage change? This reviewer suggests that the absolute change be removed because it suggests more precision that the process merits and because the percentages are more meaningful.

We agree with this and have changed to figures to only represent the percentage change.

j) p. 21, section 3.5. The new reference to the Minergie standard should be placed after Minergie building or at the end of that sentence, and not at the end of the paragraph.

Fixed.

k) p. 19, line 260. Online sources use plug load rather than plug-load. Either is better than plug- load (with both a hyphen and a space), as used in the text.

Fixed.

l) p. 24, lines 348-353. The new discussion section includes two redundancies. In the first sentence, please consider deleting on two real-world case studies, given the reference to case studies at the beginning of the sentence. The third sentence could be ended with ...unique to this case study....

The first redundancy was fixed. For the second one, we removed ”in this particular instance”, but kept the ”unique to this case study” were it is

m) p. 25, lines 368-375. In line 372, please hyphenate case-study (when used as a modifier for campuses). In line 373, please remove the space after the hyphen in co- simulation.

Fixed

n) p. 25, lines 376-379. The text identifies practical implementation of retrofit scenarios and retrofit analysis as future applications. How do these applications differ?

We removed the second reference to retrofits and, instead, changed it to refer to general ”systems analysis”

o) p. 26, line 416. Only the K in KAEMPF should be capitalized.

Fixed.

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Research Article

Urban and building multiscale co-simulation: case study implementations on two university campuses

(*Received 00 Month 20XX; final version received 00 Month 20XX*)

The co-simulation of both urban and building-level models leverages the advantages of both platforms. It better accounts for the localized effects of surrounding buildings, geography and climate conditions while maintaining high-fidelity building systems representation. This paper describes the co-simulation process of the building and urban-scale models of two university campuses in Switzerland using EnergyPlus and CitySim. In the first case study, on-site measured performance data is compared to the co-simulation results. The second case study examines the results of the two engines. The results show that coupling of EnergyPlus with CitySim resulted in a -15.5% and -7.5% impact on cooling consumption and a +6.5% and +4.8% impact on heating use as compared to solo simulations.The co-simulation process was able to better model realistic conditions for heating, but not cooling in one case study. It was able to substantially reduce the discrepancies in prediction between the engines in the other study.

Keywords: Building-scale simulation, Calibrated energy models, CitySim, Co-simulation, EnergyPlus, Urban-scale simulation

1. Introduction

Urban-scale building performance simulation is a process that empowers the analysis and optimization of cities. Urban populations are growing around the world at an unprecedented rate. A transition from urban to rural is underway and 2.5 billion people are expected to join cities throughout the world by the year 2050 (United Nations 2014). Expansions of entire districts and even cities is not an uncommon phenomenon, especially in East Asia and Africa. Urban-scale modeling is in the midst of an intense focus on the research community with six key areas of practice: technology design, building design, urban climate, systems design, policy assessment, and land use and transportation (Keirstead, Jennings, and Sivakumar 2012). The ability to simulate the interaction between large collections of buildings enables the development and testing of optimization and planning scenarios for this new development (Dorer et al. 2013).

The CitySim simulation engine is an example of such a program designed and optimized for urban-scale simulation. CitySim is an urban performance simulation engine that comprises a solver module as well as a graphical user interface. It focuses on the energy flows of multiple simplified building models and their interdependent relationship with their urban climate (Robinson et al. 2009). CitySim includes building thermal, urban radiation, occupant behavior, and plant/equipment models integrated as a single simulation engine. CitySim simulates multiple buildings up to city scale using simplified models to achieve a good compromise between modeling accuracy, computational overheads, and data availability. Each building's thermal behavior is based on an electrical analogy using a two node resistor- capacitor network. The internal lighting, people, and miscellaneous loads are modeled using a simplified occupancy-based approximation. The heating, ventilation, and air-conditioning (HVAC) systems are modeled using a set of equations that approximates the total mass flow rate required to meet the sensible and latent loads of each building as a whole. Each of these simplifying approximations empowers the urban-scale simulation to have reasonable execution times on the number of buildings being simulated.

Building performance simulation is a mature domain of research relative to urban-scale efforts.

The use of whole building simulation engines originated in the 1960's with the US government's development of the BLAST and DOE-2 hourly energy simulation programs (Lawrie et al. 2001). In 1996, development on a new simulation engine, EnergyPlus, began in order to combine the advantages of previous efforts in a single, modular program. EnergyPlus, as a result, has become a popular choice in detailed whole-building performance simulation due to the breadth of mechanical, renewable, and electrical systems that can be modeled. EnergyPlus specifically excels in its ability to model unique mechanical system types such as decoupled centralized cooling (Miller and Sekhar 2010). Additionally, EnergyPlus is designed to provide a high resolution in which internal loads and natural ventilation technologies can be modeled in detail at the building level. EnergyPlus is also extensively used within the research community and has new features that enable it to couple with other simulation programs.

Both building and urban-scale simulation domains have rightfully chosen boundary conditions that reflect their key goals while seeking to minimize the input parameters necessary and run-times of the engines themselves. This focus results in certain deficiencies concerning modeling various phenomena. For example, urban-scale simulation highly simplifies the building systems and internal load models, thus making a retrofit analysis at the systems level difficult. And whole building simulation in EnergyPlus neglects many of the various contextual consideration of the urban environment such as long-wave radiation exchange with adjacent surfaces and localized urban weather effects (Lawrie et al. 2001).

The current effort seeks to couple building and urban-scale simulation to address the deficiencies of the individual engines. The research in this paper is part of a larger coupling effort in which various engines are connected and co-simulated to create a more comprehensive analysis of the urban-scale (Dorer et al. 2013; Allegrini, Dorer, and Carmeliet 2012). The target is the computational interface between the building energy model, using EnergyPlus, and the urban energy model using CitySim. An overview of the larger scope is shown in Figure 1 and the context of the coupling task appears as the interface between the City Energy Simulation (CES) model and the Building Energy Simulation (BES) model. The scales and models contained in the urban environment context include the Urban-Scale Model (UC Model), the Urban Microclimate (UMC) model using OpenFoam, and the Meteorological Meso-scale (MM model) using Climate Limited-Area Modeling (COSMO-CLM). On the database side, Revit, Global Information Systems (GIS), and building information systems (BIS) are utilized.

The coupling and co-simulation process is implemented on two case studies in Switzerland. The first case study is the ETH Zürich Hoenggerberg campus in Zürich, Switzerland. It was modeled in the CitySim simulation engine and co-simulated using work-flow automation. The target of this case study is to evaluate the differences between the coupled and solo EnergyPlus simulations based on the variables exchanged. This scenario includes the use of measured data for heating and cooling within their respective seasons to compare to the simulation results. The second case study is the EPFL campus in Lausanne, Switzerland. The objective of this scenario is to evaluate the differences between coupled and uncoupled versions of the CitySim simulation engine.

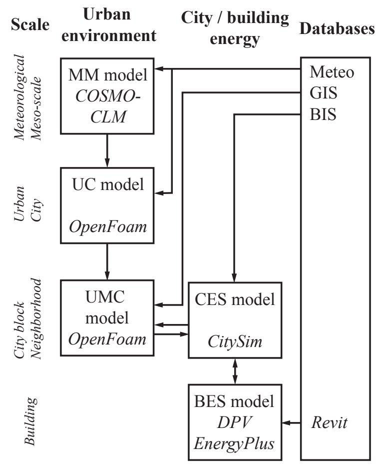

Figure 1. EnergyPlus and CitySim coupling are part of the wider context. Each block in the diagram represents an environment, with the tool/engine name in italics ((Thomas et al. 2014), adapted from (Dorer et al. 2013))

This paper describes the achievement of several objectives. The first is to automate the process of simultaneous meta-data extraction from a Building Information Model (BIM) for the creation of both building and urban-scale performance models for a real-world campus of buildings. Next, we co-simulate the urban and building scale models through concurrent information exchange. Finally, we implement a simplified calibration procedure for the first scenario by reconciling the co-simulation output results for a target building using measured energy performance data from the campus energy information system (EIS)

The first two objectives have been demonstrated in a simplified context in previous literature (Thomas and Schlueter 2012; Miller et al. 2015). The innovation in the current publication is an extension of this research through the modeling and co-simulation of real-world case studies. With respect to the third contribution, to the best of the authors' knowledge, no previous study has compared the results of a building and urban-scale co-simulation procedure to measured data from a real-world campus.

1.1. *Previous multi-scale coupling studies*

Previous attempts of information exchange have been implemented between simulation engines at various scales. Much of the initial co-simulation work in the literature is done at the subsystem and building-scale. Previous studies have analyzed strong and loose coupling of engines at this scale (Wetter 2011; Trčka, Hensen, and Wetter 2010). Coupling of building-scale simulation with urban-scale computational fluid dynamics (CFD) is attempted for modeling natural ventilation (Zhang et al. 2013) and to improve energy prediction (Bouyer, Inard, and Musy 2011). A comprehensive review of energy and airflow modeling of neighborhoods and university campuses was published that includes strategic aspects of coupling different types of models (Srebric, Heidarinejad, and Liu 2015). EnergyPlus has been coupled with ENVI- met, a micro-climate computational fluid dynamics (CFD) program (Yang et al. 2012). It was also coupled with simplified lumped parameter models to facilitate comparison with measured sensor data (Martin et al. 2015). While not directly coupled, EnergyPlus and the TEP Urban Canopy Model program were connected through a modified weather file to quantify the influences of urban localized weather effects on whole building simulation (Bueno et al. 2011).

2. Methodology

2.1. *Coupling process*

The coupling process of a simplified single zone model and contextual surrounding buildings is described in previous studies (Thomas et al. 2014), which forms the basis for the methodology in the current effort. This process utilizes the Design Performance Viewer (DPV) and associated workflow. The DPV is a tool written to extract and simulate an EnergyPlus input data file (IDF) from an Autodesk™ Revit™ BIM (Schlueter and Thesseling 2009). The central philosophy behind the tool is the rapid simulation of the building information model from the earliest design possible that can be used throughout the life-cycle of the building including retrofit analysis (Miller et al. 2014). This process is achieved by augmenting the information in the BIM with default values and abstracting information not relevant for energy simulation. The tool already has a simplified notion of surrounding buildings, which are modeled in the BIM as simple mass objects without further information and are exported as shading surfaces to EnergyPlus. This functionality is used for creating the CitySim mass scene and leads to a crude model of the urban context of the building. The current DPV philosophy of allowing the designer to iterate rapidly on early design decisions based on feedback about the performance of the design remains. This approach includes streamlining the process where running a simulation requires no effort from the designer due to automatic creation of input files, execution, and analysis of the results.

The coupling process of EnergyPlus and CitySim is shown in Figure 2. The solid lines depict the co-simulation of EnergyPlus and CitySim, and the dotted lines illustrate solo simulations of either EnergyPlus or CitySim. First, the DPV is used to extract an EnergyPlus simulation model from the BIM. The DPV utilizes the Revit API to extract geometrical information about the building and the physical properties of walls, windows, doors, roofs, and floors. This information is encoded in the BIM model as wall types, roof types, floor types as well as window and door families. Wherever possible, the tool uses the layering and materials of the construction types, enhancing them with physical attributes relevant to EnergyPlus. Where not defined, it assumes default values.

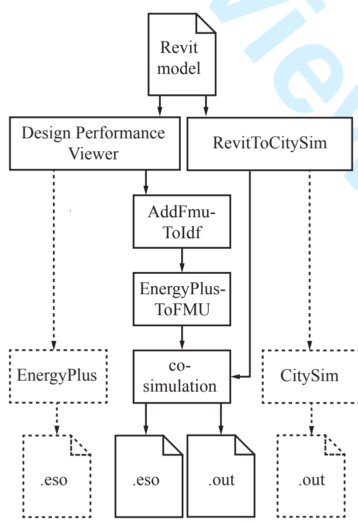

Figure 2. Overview diagram of the coupling process including tools and outputs (Thomas et al. 2014)

Next, geometry is created to be used in both the CitySim and EnergyPlus models as buildings and surfaces surrounding the building targeted in the IDF. This feature of the DPV is used for including shading surfaces in the EnergyPlus simulation model: it uses so-called *mass objects* in the BIM model as surrounding buildings. The DPV model views these buildings as a series of shading surfaces. A transformation is added to the DPV model that produces an input file for the CitySim

solver. This file uses an XML format describing the buildings in a scene for simulation, including their construction types, geometry, and systems for heating and cooling. The main BIM is extracted to the CitySim scene as one of the buildings to be simulated, with the properties of the construction types matching those in the DPV model. The glazing ratio is calculated based on the window and wall areas of the DPV model. Shading surfaces are grouped into buildings based on the mass object from which they were extracted. These adjacent buildings use default construction properties for walls and roofs, and we assign them a default glazing ratio. These defaults can be overridden by custom properties applied to the mass objects in the BIM much in the same way as the model elements of the main building are enriched with DPV information.

As of version 8.1.0, EnergyPlus supports exporting a simulation model as a Functional Mock-up Unit (FMU) (Nouidui, Wetter, and Zuo 2014). This feature introduces new IDF objects to specify the interface such an FMU exposes. These objects define which output variables are exported by the FMU and which variables are imported. The FMU export functionality is closely linked to the Energy Management System (EMS) of EnergyPlus. Co-simulation exchange variables either mimic an EnergyPlus schedule, an EMS variable or drive an EMS actuator. Since the model used by CitySim to simulate a building is more abstract than the model used by EnergyPlus, the EMS is used to aggregate certain values. CitySim does not model windows separately. Therefore, a weighted average of window and wall surface temperatures is calculated with EMS subroutines.

The FMU creation process is the basis for coupling the two models at each timestep in the simulation. Figure 3 illustrates this process from both the EnergyPlus and CitySim perspective. The augmented IDF file is fed to the *EnergyPlusToFMI* script (Nouidui and Wetter 2014). Once configured, this script produces an FMU file based on the augmented IDF file and the weather file to be used as well as a DLL file implementing the Functional Mock-up Interface that can load the IDF file, locate EnergyPlus and run the simulation.

The number of timesteps for both CitySim and EnergyPlus is set to one per hour. The frequency of data exchanges is set to once per timestep. No data averaging over time is performed. Data exported from one simulation engine overwrites the corresponding data in the other simulation engine at each timestep. Each simulation is performed for a whole year.

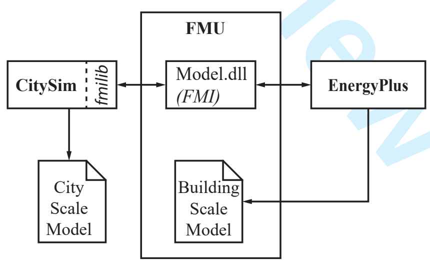

Figure 3. Simulation information exchange between CitySim and EnergyPlus using FMI (Thomas et al. 2014)

2.2. *Coupled variables*

Several key urban-scale weather variables are sent to EnergyPlus from CitySim to account better for the localized effects of surrounding buildings, geography and climate conditions. These variables are outlined in Table 1. They include various outdoor air conditions such as dry bulb and wet bulb temperatures, dew-point, humidity, wind speed and direction, and direct and diffuse solar radiation. These variables overwrite the input weather variables that EnergyPlus obtains from its weather file input. CitySim is designed to account for physical phenomenon inherent to urban environments, which are often neglected in building-scale simulation environments (Robinson and Stone 2004; Robinson et al. 2009). CitySim can be connected to a simplified micro-climate airflow model that can predict local climatic conditions around each building. Long-wave radiation exchange between the simulated building and its surroundings is sent to EnergyPlus; this process is described in detail in Section 2.3. Finally, CitySim shares its calculated occupancy schedules as it can use a deterministic or stochastic occupant behavior model, whereas EnergyPlus models are solely a deterministic models (Haldi and Robinson 2011).

Table 1. Values sent to EnergyPlus from CitySim by the FMU

Object	Variable Name	Description
Outdoor	Outdoor Drybulb	The outdoor dry-bulb temperature in °C
	Outdoor Dewpoint	The outdoor dewpoint temperature in °C
	Outdoor Relative Humidity	The outdoor relative humidity expressed in percent.
	Diffuse Solar	Diffuse horizontal irradiance in W/m^2
	Direct Solar	Beam normal irradiance in W/m^2
	Wind Speed	The outdoor wind speed in m/s
	Wind Direction	The wind direction in degrees (N=0, E=90, S=180, W=270)
Long-Wave Radiation	Environmental Radiant Temp.	Calculated T_{env} from the sky, ground, and surrounding surfaces
	Environmental Radiant Heat Gain Coefficient	Calculated h_{env} from the sky, ground, and surrounding surfaces
Zone	Occupation	Fraction of the maximum occupation (0.0-1.0) overrides the EnergyPlus occupation schedule with the CitySim stochastic schedule.

Variables sent to CitySim by EnergyPlus at each time step include several variables related to the calculation of heating and cooling loads of a targeted building. Table 2 outlines this list of exchanged variables. These variables are transferred due to the ability of EnergyPlus to model more detailed building systems, schedules, ventilation and internal load types than CitySim. For example, EnergyPlus is flexible enough to model a detailed radiant heating and cooling system that would be impossible in CiytSim. EnergyPlus is an engine optimized to accurately model building-scale systems. Thus, CitySim can take advantage of these models through coupling and co-simulation. EnergyPlus sends the heating and cooling loads, the surface temperatures of the exterior surfaces and the ventilation flow rates to CitySim.

Table 2. Values sent to CitySim from EnergyPlus by the FMU

Object	Variable Name	Description
Wall, Roof	Outside Surface Temperature	The temperature on the outside of the surface in °C
Wall	Average Outside Surface Temperature	The (weighted) average temperature of the surface on the outside in °C.
Zone	Total Heating Energy	The heating energy in Joules used in this timestep.
	Total Cooling Energy	The cooling energy in Joules used in this timestep.
	Zone Mean Air Temperature	The mean air temperature in the zone in °C
	Ventilation Volume Flow Rate	The flow rate in m^3/s (standard density)

2.3. *Long-wave radiation exchange*

Long-wave radiation exchange in the urban-scale environment is coupled in the co-simulation process. It requires the development of a set of approximations to reduce the number of coupled variables between the engines and to account for differences in the methods by which each engine calculates this value. A detailed description of Long-wave Radiation (LWR) variable exchange and approximation is found in a previously published study (Miller et al. 2015) on a simplified theoretical case.

In EnergyPlus, LWR exchange for a surface is calculated through the summation of radiation gain from the ground, sky, and air as seen in Equation 1 and Figure 4a (United States Department of Energy (DOE) 2015). The radiant heat transfer coefficient for each of these environmental variables is calculated according to Equation 2 with σ as the Stefan-Boltzmann constant, ϵ as the emissivity and $F_{variable}$ being the view factor to the variable that can be sky, grd (ground) or air. A major assumption of this approach is that the modeled building's surfaces and those of adjacent buildings are at a uniform temperature and the LWR radiation exchange is negligible; a situation that is an

oversimplification in an urban scale domain (Evins, Dorer, and Carmeliet 2014).

$$Q_{LWR,EnergyPlus} = h_{r,grd}(T_{surf} - T_{grd}) + h_{r,sky}(T_{surf} - T_{sky}) + h_{r,air}(T_{surf} - T_{air}) \tag{1}$$

$$h_{r,variable} = \frac{\epsilon\sigma F_{variable}(T_{surf}^4 - T_{variable}^4)}{T_{surf} - T_{variable}} \tag{2}$$

In comparison, CitySim calculates LWR exchange by calculating an aggregated equivalent temperature, T_{env}, and radiative heat transfer coefficient, $h_{r,env}$, from surrounding urban surfaces in addition to ground, sky, and air (Robinson et al. 2009). The calculation for T_{env} is expressed in Equation 3 with the F values being view factors of the surrounding environment including adjacent surfaces $i = 1..n$. $h_{r,env}$ is based on a first order Talyor development of the numerator of Equation 2 around $(T_{surf} + T_{variable})/2$ and therefore $Q_{LWR,CitySim}$ is calculated using Equation 4.

$$\sigma T_{env}^4 = \sigma F_{sky} T_{sky}^4 + \sigma F_{grd} T_{grd}^4 + \sum_{i=1}^{n} \epsilon_i \sigma F_i T_i^4 \tag{3}$$

$$Q_{LWR,CitySim} = h_{r,env}(T_{surf} - T_{env}) \tag{4}$$

In the coupled simulation, EnergyPlus uses the CitySim supplied equivalent $h_{r,env}$ and T_{env} to calculate weighted $h_{r,sky}$, $h_{r,grd}$, and $h_{r,air}$ values using the view factors and the sky-to-air split ratio. Figure 4 illustrates the schematic differences between the solo and coupled simulations on a theoretical example of a target building with two adjacent buildings with surfaces available for radiation exchange.

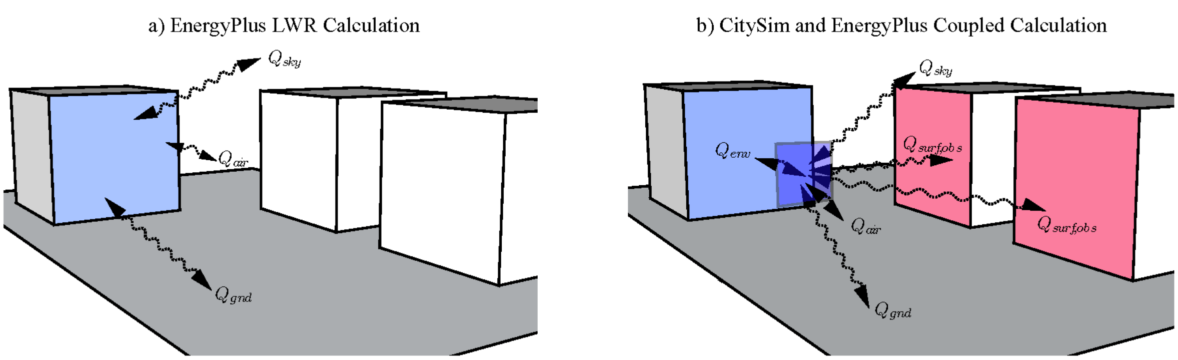

Figure 4. Comparison of the LWR components between a) Solo EnergyPlus and b) Coupled CitySim/EnergyPlus configuration (Miller et al. 2015)

2.4. *Work flow automation*

The coupling, simulation and co-simulation process is completely managed within a program called VisTrails (Freire et al. 2014). The implementation of this type of workflow is outlined in previous work focused on automating DPV using the Kepler platform (Thomas and Schlueter 2012). This process reduces the effort expended by a designer down to pressing a single button. This functionality allows an iterative design informed by readily available simulation results. An automated workflow ties the various steps together and maintains the effortless iterative design process. VisTrails enables the coupling of various workflow subprocesses script initializations, executions of the engines, and

the compilation of the outputs. This tool empowers the coupling of multiple executable files and their connecting scripts in graphical diagrams that enhance reproducibility and process automation (Freire et al. 2014). The VisTrails workflow diagram for the first case study in this paper is seen in Figure 5.

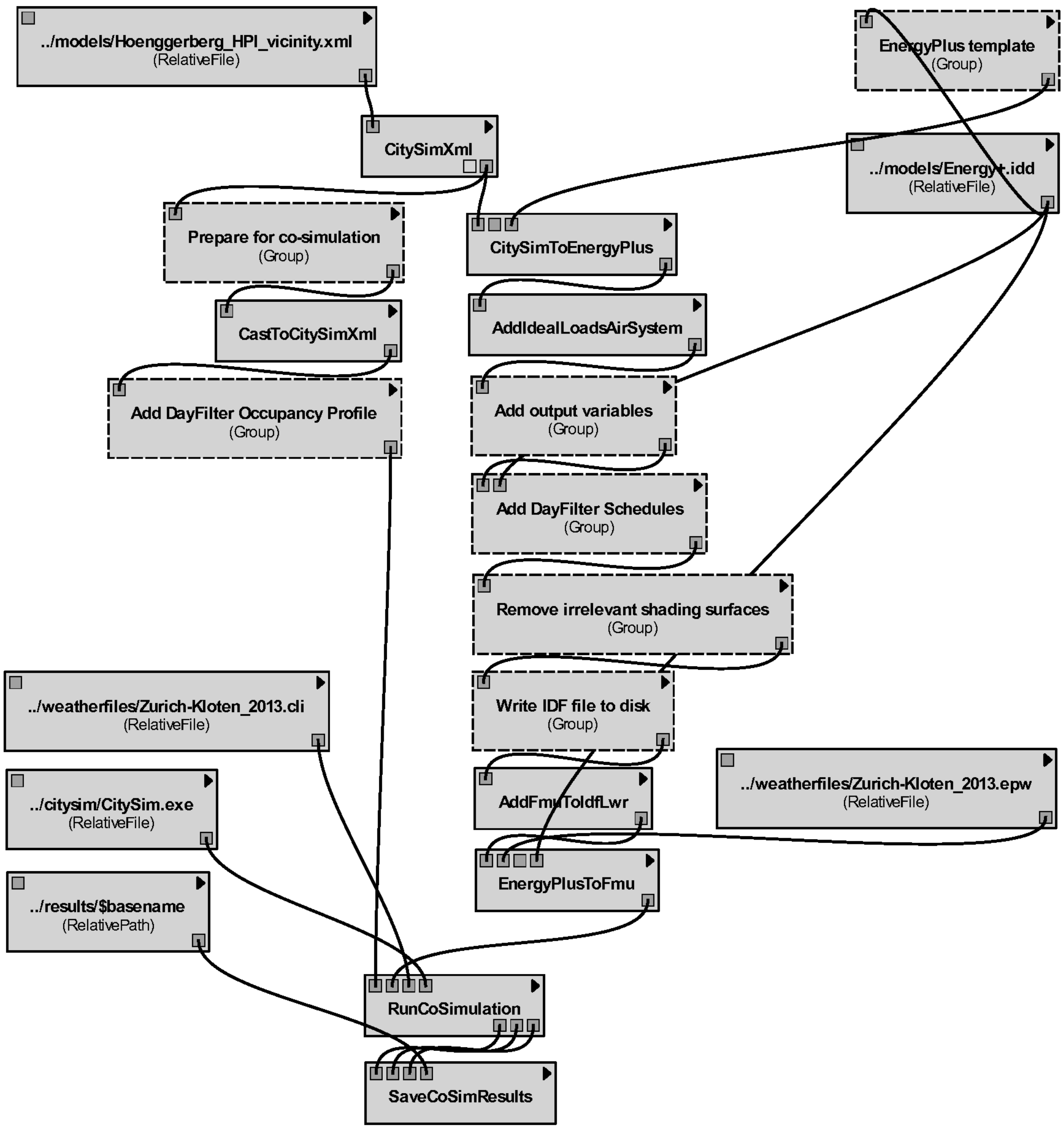

Figure 5. Workflow in VizTrails

2.5. *Simplified calibration*

In the first case study, one aspect of this analysis is the comparison of the actual measured performance of the target building on campus with the results of the co-simulation. A simplified calibration procedure is adapted from previous research to compare the measured heating and cooling data available on campus with various simulation scenarios (Samuelson, Ghorayshi, and Reinhart 2015). This calibration procedure was utilized in the performance reconciliation of 18 buildings that were built according to the LEED Canada protocol and were under review of actual performance. This protocol is unique in its analysis process to uncover design model deficiencies in a step-wise manner, utilizing the most readily available knowledge first and working towards equilibrium between measurement and simulation. There is an appropriate balance between the effort of implementation and value generated through the calibration process.

3. Implementation

The co-simulation process is implemented on two case studies in Switzerland. The first is the ETH Zürich Hoenggerberg campus in Zürich, Switzerland. The focus of this case study is to quantify the impact of the information exchange through co-simulation within the EnergyPlus engine. The intent on this campus was to develop techniques for retrofit analysis using EnergyPlus. The targeted building on this campus is the HPI Building. Raw measured data is available for many of the buildings on campus, thus a simplified calibration procedure is used to reconcile the simulation results.

The second case study is the EPFL campus in Lausanne, Switzerland. The targeted building, in this instance, was the Quartier Nord complex. The focus of this study was to compare the solo and co-simulation output results of CitySim. Reliable measured data for calibration is not currently available for this building.

3.1. *Campus case study 1: ETHZ Hoenggerberg Campus*

The ETH Zürich Hoenggerberg campus includes 32 higher education facilities with spaces allocated to laboratories, office space, lecture halls, cafeterias, data centers and other types of similar areas. The campus has a centralized energy management system (EMS) that contains 807 energy and water measurement points from heating, cooling, electricity, city gas, domestic hot water, gray water, and general water consumption.

The focus of the co-simulation process is that the performance of a targeted building is evaluated through solo and coupled methods. The HPI building on campus was chosen in this case study due to the amount and quality of measured data available from the EMS for this building. HPI is a 2,610 square meter building that is made up mostly of office space and classrooms. It also includes 400 m^2 convenience store and coffee shop. The building is indicated on a campus map shown in Figure 6 and is shaded red.

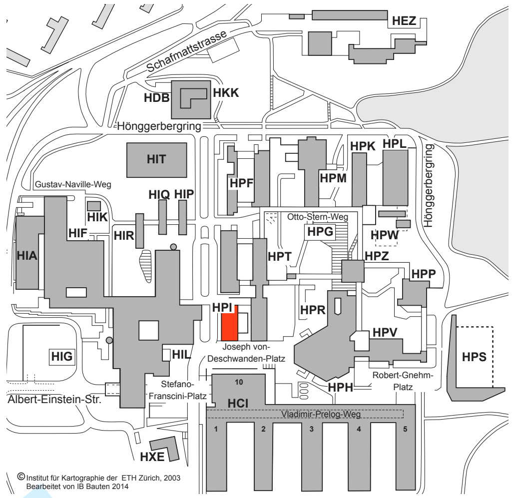

Figure 6. ETH Hoenggerberg campus map with the HPI building shaded red

3.2. *Model development*

In order to perform a co-simulation of the targeted buildings, initially a CitySim model of the campus was developed. Through the workflow automation process, this geometry was converted into an EnergyPlus input file as seen in Figure 7. The EnergyPlus input file was then used as an input to execute EnergyPlus solo and co-simulation processes for the purpose of simplified calibration, and then to understand the magnitude of the difference between these simulation scenarios.

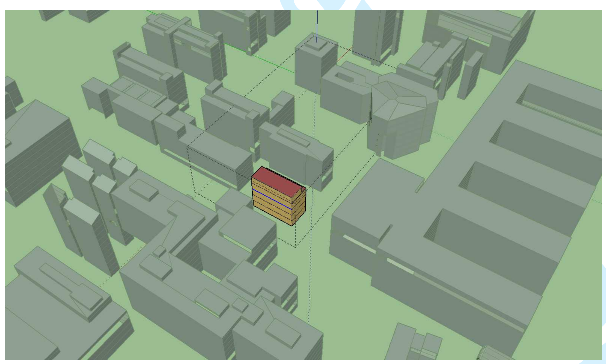

Figure 7. The HPI building EnergyPlus model extracted from the CitySim model. The HPI building is seen as the light and dark brown building in the center surrounded by gray masses that represent other buildings on campus. The graphic is illustrated with OpenStudio for Sketch-up.

3.3. *Measured data collection and calibration*

Energy data from the HPI building was collected and analyzed in the context of the simplified calibration procedures. The measured datasets were screened and aggregated into typical usage profiles to be used for the lighting, plug loads, and HVAC equipment availability schedules and power densities. Figure 8 illustrates the aggregation examples of electrical energy for the HPI building. This profile was created through a filtering and clustering process known as *DayFilter* (Miller, Nagy, and Schlueter 2015). Cluster 0 represents the typical energy profile for Sunday, while Cluster 1 dominates the Saturdays of the data set. Clusters 2 and 3 make up most of the weekdays of the data set with Cluster 3 being more common in non-summer months. These profiles are used to set the availability schedules as inputs into the EnergyPlus simulation to emulate the way occupants inhabit the building and how the building management system (BMS) controls the lighting and HVAC systems.

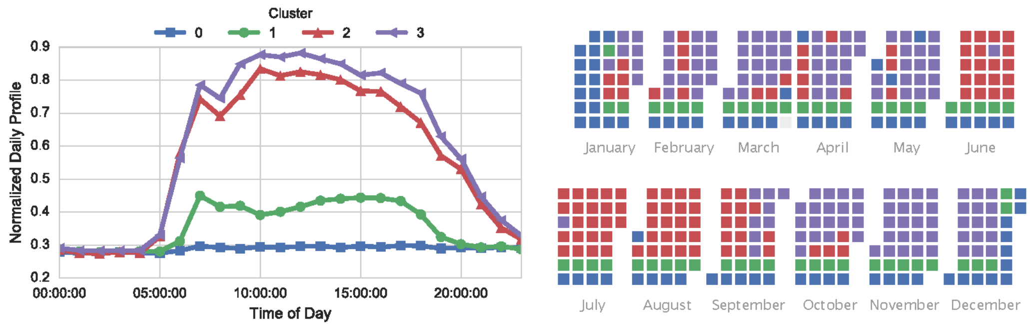

Figure 8. Typical measured data electricity profiles of (left) average daily electrical consumption for each cluster and (right) color-coded calendar of which days fall within each cluster. The diagram on the right is each month of the year with each row corresponding with a day of the week (starting with Monday) and each column corresponding to a week of the month.

The measured and simulated data from both the co-simulation and EnergyPlus solo simulation were analyzed in order to understand how both the solo and co-simulations compare to real, measured data. The calibration process was undertaken through a series of steps such as including local weather conditions for the simulation period and adding custom lighting schedules and power densities extracted from the measured data. The models were calibrated to the summer season (May-September) for cooling and the winter season (Jan-April and October to December) for heating. Figure 9 illustrates a comparison of the measured data with the simulations after the tuning process. The final calibrated EnergyPlus solo model had a normalized mean bias error (NMBE) of -9.36% and a coefficient of variation of root mean square error (CVRMSE) of 21.7% for cooling and 5.02% and 29.4% for heating. These metrics fall within the +/-10% NMBE and +/-30% CVRSME used in this case study for calibration. A total of 37 calibration iterations were undertaken to modulate the simulation results to within these criteria. The goal of calibration, in this case, is to just bring the models to within a reasonable range of reality in order to bring more confidence to analysis of the discrepancies between the solo and co-simulation scenarios.

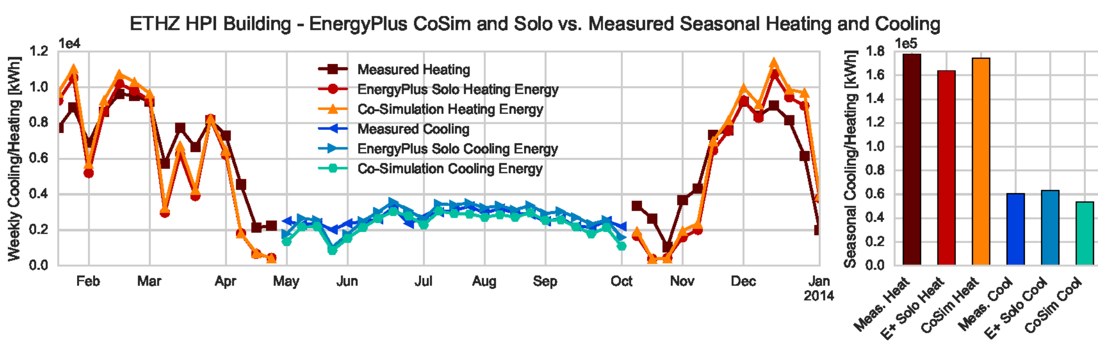

Figure 9. HPI Measured vs. Co-Simulation and EnergyPlus Solo for Heating and Cooling Seasons

3.4. *EnergyPlus co-simulation results*

For cooling, a discrepancy can be seen between co-simulation and solo EnergyPlus. Co-simulation decreases the predicted cooling energy by 15.5%, as seen in Figure 10. Figure 11 illustrates the difference in predicted heating energy consumption across the test year. A consistent offset exists across the time frame of days in January, the peak of the heating season. A more varied discrepancy across the heating months is noticed resulting an overall increase of heating prediction of 6.5% due to co-simulation. The exchange of long-wave radiation for this particular site is substantial due to the proximity of surrounding buildings.

When comparing the solo and co-simulated models to the measured data, it is noticed that cooling energy is over-predicted by the solo simulation by 4%, while co-simulation under-predicted by 11.1%. This discrepancy is likely due to a loss in long-wave radiation in the co-simulation to the surrounding buildings, thus reducing the overall cooling load.

For heating energy, co-simulation was able to bring the predicted value to within 2% of the measured value for the year, an improvement as compared to the solo simulation, which was 8.5% less than the measured value. This situation is also likely due to the long-wave radiation loss to surrounding buildings, thus increasing the overall heating load.

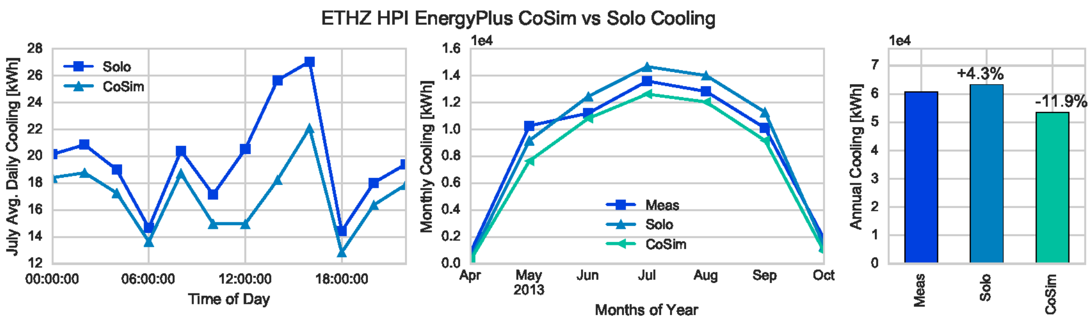

Figure 10. HPI Co-Simulation vs. EnergyPlus Solo for Cooling

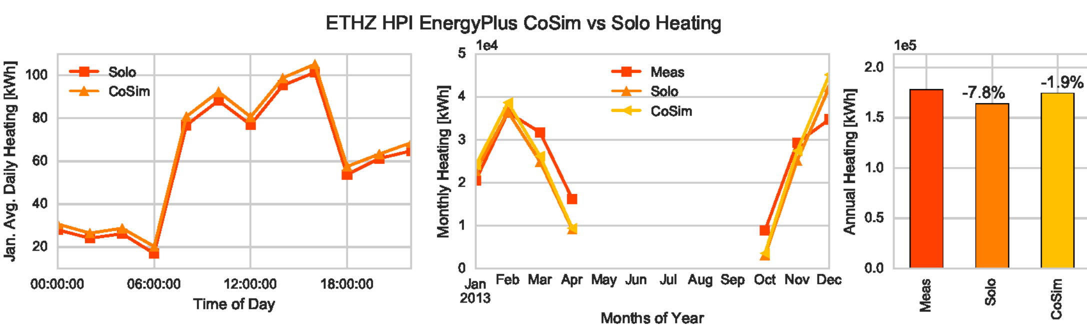

Figure 11. HPI Co-Simulation vs. EnergyPlus Solo for Heating

3.5. *Campus case study 2: EPFL Quartier Nord*

Quartier Nord is a whole new quarter of the École Polytechnique Fédérale de Lausanne (EPFL) campus located at its northwest corner. This complex includes a Convention Centre with an auditorium with a maximum capacity of 3000 (seated) people, housing for 516 students, retail and service areas and a hotel. As a public space, this ensemble is organized around the central plaza as seen in Figure 12). With a particularly strong visual and formal identity, the SwissTech Convention Centre (STCC) is clearly the key protagonist. Designed as a Minergie building, it includes modern energy conversion technologies to reduce its energy consumption (Beyeler, Beglinger, and Roder 2009). The focus of the co-simulation is realized on the STCC, simulated with the nearby buildings for housing, retail and service areas.

Figure 12. The Quartier Nord at EPFL in Lausanne

3.6. *Model development*

The information required in the simulation mainly comprises three parts: physical, geometrical and operational data. The geometry information including the shape, dimension, structure and materials was obtained from the Real Estate and Infrastructure Department of École Polytechnique Fédérale de Lausanne (EPFL), which was responsible for carrying out the project from call to tender to construction. However, since the documents provided were conflicting with what has been installed, the task to realize a precise model of the buildings itself is rather tedious. Besides, it is even more challenging to get the operational data (daily occupancy, lighting, and electrical equipment usage level and ventilation rate) as the building has only recently been set in operation mode and as engineers and technicians have been working on improving the controls. Therefore, due to unreliable monitoring data, the calibration step of the model was not undertaken.

Considering the lack of detailed information about the building, a so-called detailed reference case was modeled with EnergyPlus (Mauree et al. 2015) in which regulation standards applied in the design phase from the local building code norms were used to complete the missing information. A rendering of this model is seen in Figure 13.

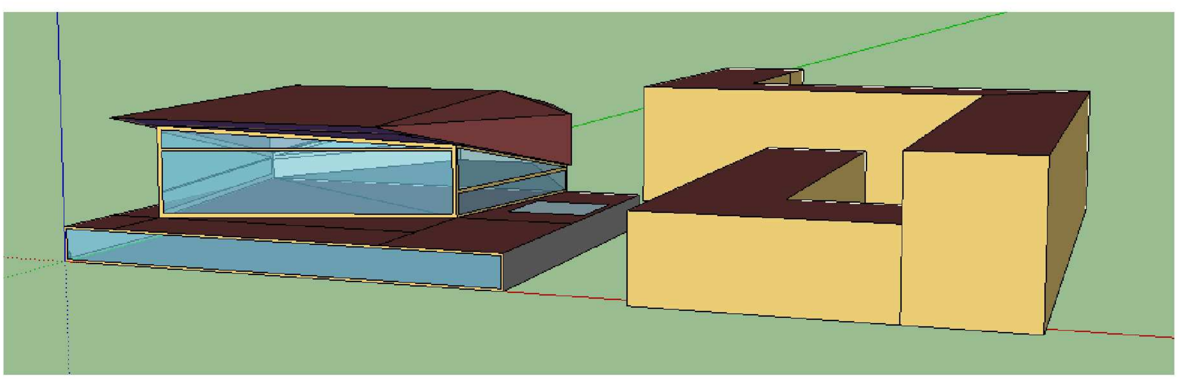

Figure 13. The Quartier Nord modeled with OpenStudio for Sketchup[2]. The STCC on the left is the main focus of the study and is represented by two thermal zones.

The corresponding CitySim model was created by exporting a DXF file from EnergyPlus for the whole of Quartier Nord, and importing it into the Graphical User Interface of CitySim. Physical characteristics of the building were added to complete the CitySim model. Finally, the same script as described in Section 2 was used to export the model from CitySim to EnergyPlus, giving a simplified EnergyPlus model.

3.7. *Comparison of EnergyPlus and CitySim*

Both the CitySim and EnergyPlus engines are utilized in this case study. The first comparison to observe is the differences between the two engines when focused on the STCC building. When simulated in isolation, the CitySim engine predicts a 28.6% increase in heating load and a 44.4% increase in cooling load as compared to EnergyPlus. This phenomenon is due to the differences in the way each of these engines calculates heating and cooling loads. CitySim has a much more simplified model of building occupants, lighting, and plug loads. CitySim also includes long-wave radiation exchange calculations that can greatly influence the heating and cooling load calculations as well. Use of the co-simulation process brings the engines to within 5.4%. Figure 14 illustrates these differences for cooling and Figure 15 for heating.

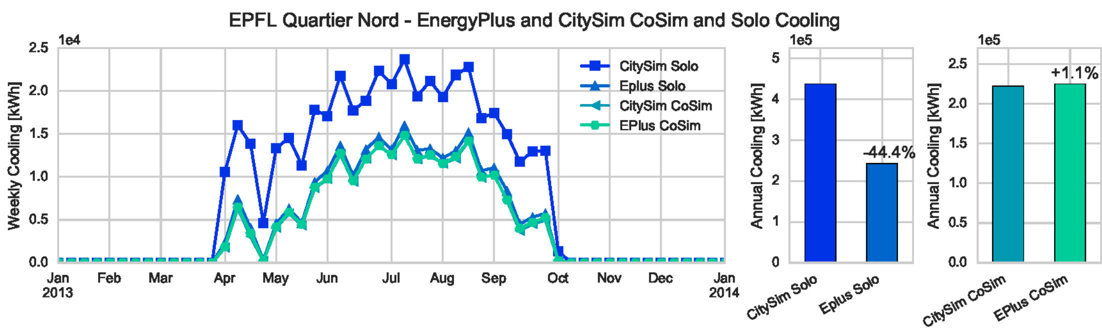

Figure 14. STCC CitySim vs. EnergyPlus Solo for Cooling

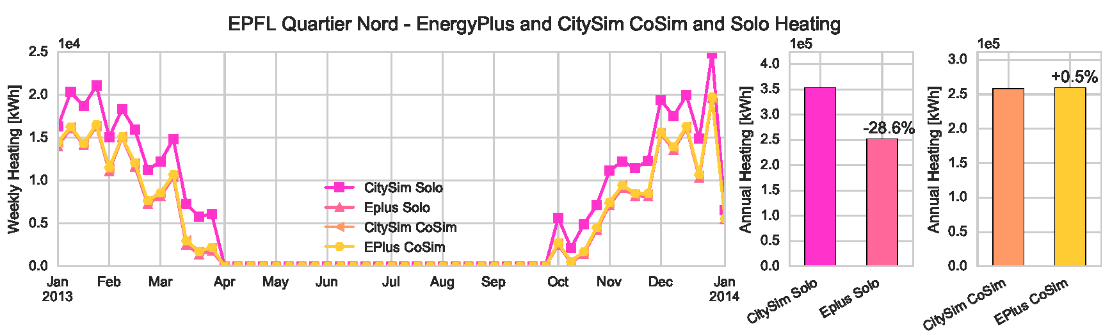

Figure 15. STCC CitySim vs. EnergyPlus Solo for Heating

3.8. *EnergyPlus co-simulation results*

The STCC building is also simulated within the solo and co-simulation environments. When focusing on the EnergyPlus results, a 7.5% decrease in cooling energy is observed, as seen in Figure 16. A 2.8% increase in heating energy is observed, as seen in Figure 17. These differences are less pronounced than the HPI and theoretical case studies due to the number and proximity of surrounding buildings is not as large. long-wave radiation exchange in this situation doesn't have as large of an impact on the heating and cooling calculations.

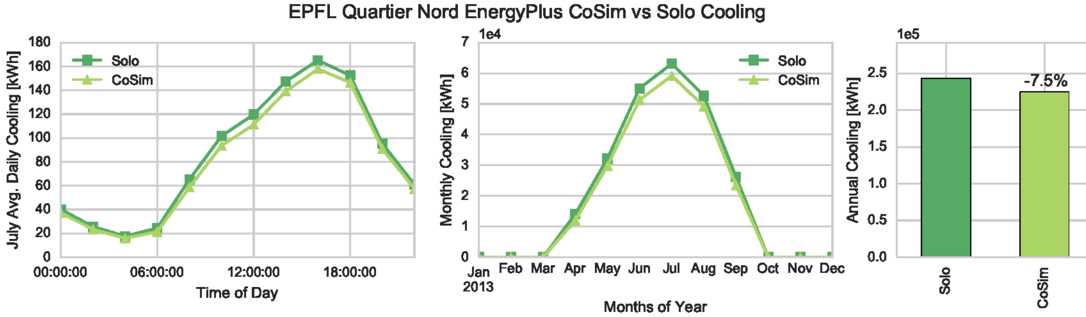

Figure 16. Quartier Nord EnergyPlus Co-Simulation vs. Solo for Cooling

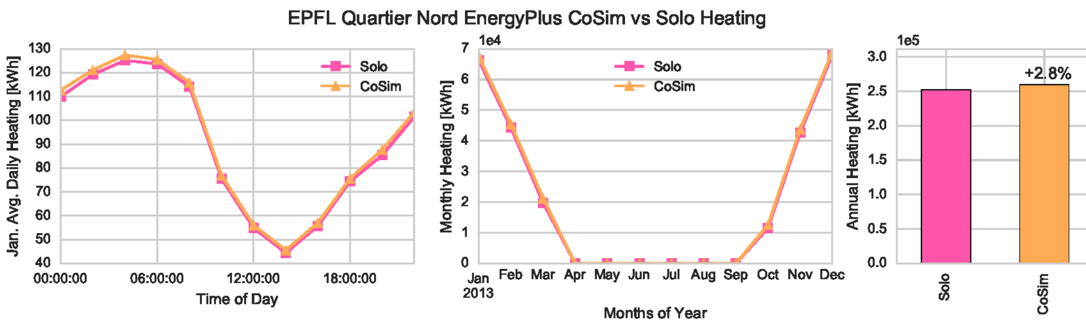

Figure 17. Quartier Nord EnergyPlus Co-Simulation vs. Solo for Heating

4. Discussion

Two campus case studies were presented in this paper to showcase a unique process of extracting model meta-data, conversion of those data into input files for two separate simulation engines, and the solo and co-simulation process of those engines. The analysis of the results shows that for the first case study, co-simulation can achieve values closer to measured reality for heating, but not cooling. These results are unique to this case study and simply show that the co-simulation process may be helpful for heating only. A limitation of this study is that we only analyze a single building against measured data in this context. In the second case study, significant discrepancies are found between the CitySim and EnergyPlus engines which were corrected using the co-simulation process.

One of the key insights in this work is that each of the engines is enabled to account for the various physical phenomenon in their simulation process that were previously impossible. For example, through co-simulation, EnergyPlus was able to utilize the long-wave radiation exchange capabilities of CitySim. The ability to couple and leverage the best aspects of multiple simulation engines can enhance the modeling of large-scale urban agglomerations.

Disadvantages of the co-simulation process are mainly centered upon the increase in computing time and power needed for the FMI to coordinate data exchange between the two simulation engines. After calibration, a comparison of the run-times of the co-simulation and solo EnergyPlus simulations show that the execution time for the solo EnergyPlus simulation was 1 minute and 49 seconds compared to 28 minutes and 10 seconds for the co-simulation.

5. Conclusion

This paper outlines the implementation of a fully automated work flow process that extracts geometry information at the urban-scale, creates the necessary input information, executes each engine with information exchange at each time step of targeted variables, and accumulates the results of the analysis. The process has been implemented on simplified theoretical scenarios in the past, and the key innovation with this work is in implementation on actual case-study campuses and targeted buildings. The results illustrate that the differences between the co-simulation and solo environments are within range of previous theoretical models. More reliable results of the magnitude of differences between the simulation techniques can be extracted from these real-world scenarios.

Future work in using co-simulation models for buildings and campuses would more intensively utilize the model results in a practical implementation of retrofit scenarios or urban-scale energy systems research. More implementations would also test the feasibility of using co-simulation for systems analysis, urban planning studies, and cooling and heating system optimization.

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Research Article

Urban and building multiscale co-simulation: case study implementations on two university campuses

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The co-simulation of both urban and building-level models leverages the advantages of both platforms. It better accounts for the localized effects of surrounding buildings, geography and climate conditions while maintaining high-fidelity building systems representation. This paper describes the co-simulation process of the building and ~~urban scale~~ urban-scale models of two university campuses in Switzerland using EnergyPlus and CitySim. In the first case study, on-site measured performance data is compared to the co-simulation results. The second case study examines the results of the two engines. The results show that coupling of EnergyPlus with CitySim resulted in a -15.5% and -7.5% impact on cooling consumption and a +6.5% and +4.8% impact on heating use as compared to solo simulations.The co-simulation process was able to better model realistic conditions for heating, but not cooling in one case study. It was able to substantially reduce the discrepancies in prediction between the engines in the other study.

Keywords: Building-scale simulation, Calibrated energy models, CitySim, Co-simulation, EnergyPlus, Urban-scale simulation

1. Introduction

~~Urban scale~~ Urban-scale building performance simulation is a process that empowers the analysis and optimization of cities. Urban populations are growing around the world at an unprecedented rate. A transition from urban to rural is underway and 2.5 billion people are expected to join cities throughout the world by the year 2050 (United Nations 2014). Expansions of entire districts and even cities is not an uncommon phenomenon, especially in East Asia and Africa. ~~Urban scale~~ Urban-scale modeling is in the midst of an intense focus on the research community with six key areas of practice: technology design, building design, urban climate, systems design, policy assessment, and land use and transportation (Keirstead, Jennings, and Sivakumar 2012). The ability to simulate the interaction between large collections of buildings enables the development and testing of optimization and planning scenarios for this new development (Dorer et al. 2013).

The CitySim simulation engine is an example of such a program designed and optimized for urban-scale simulation. CitySim is an urban performance simulation engine that comprises a solver module as well as a graphical user interface. It focuses on the energy flows of multiple simplified building models and their interdependent relationship with their urban climate (Robinson et al. 2009). CitySim includes building thermal, urban radiation, occupant behavior, and plant/equipment models integrated as a single simulation engine. CitySim simulates multiple buildings up to city scale using simplified models to achieve a good compromise between modeling accuracy, computational overheads, and data availability. Each building's thermal behavior is based on an electrical analogy using a two node resistor- capacitor network. The internal lighting, people, and miscellaneous loads are modeled using a simplified occupancy-based approximation. The heating, ventilation, and air-conditioning (HVAC) systems are modeled using a set of equations that approximates the total mass flow rate required to meet the sensible and latent loads of each building as a whole. Each of these simplifying approximations empowers the urban-scale simulation to have reasonable execution times on the number of buildings being simulated.

Building performance simulation is a mature domain of research relative to ~~urban scale~~ urban-scale efforts. The use of whole building simulation engines originated in the 1960's with the US government's development of the BLAST and DOE-2 hourly energy simulation programs (Lawrie et al. 2001). In 1996, development on a new simulation engine, EnergyPlus, began in order to combine the advantages of previous efforts in a single, modular program. EnergyPlus, as a result, has become a popular choice in detailed whole-building performance simulation due to the breadth of mechanical, renewable, and electrical systems that can be modeled. EnergyPlus specifically excels in its ability to model unique mechanical system types such as decoupled centralized cooling (Miller and Sekhar 2010). Additionally, EnergyPlus is designed to provide a high resolution in which internal loads and natural ventilation technologies can be modeled in detail at the building level. EnergyPlus is also extensively used within the research community and has new features that enable it to couple with other simulation programs.

Both building and urban-scale simulation domains have rightfully chosen boundary conditions that reflect their key goals while seeking to minimize the input parameters necessary and run-times of the engines themselves. This focus results in certain deficiencies concerning modeling various phenomena. For example, ~~urban scale~~ urban-scale simulation highly simplifies the building systems and internal load models, thus making a retrofit analysis at the systems level difficult. And whole building simulation in EnergyPlus neglects many of the various contextual consideration of the urban environment such as long-wave radiation exchange with adjacent surfaces and localized urban weather effects (Lawrie et al. 2001).

The current effort seeks to couple building and ~~urban scale~~ urban-scale simulation to address the deficiencies of the individual engines. The research in this paper is part of a larger coupling effort in which various engines are connected and co-simulated to create a more comprehensive analysis of the ~~urban scale~~ urban-scale (Dorer et al. 2013; Allegrini, Dorer, and Carmeliet 2012). The target is the computational interface between the building energy model, using EnergyPlus, and the urban energy model using CitySim. An overview of the larger scope is shown in Figure 1 and the context of the coupling task appears as the interface between the City Energy Simulation (CES) model and the Building Energy Simulation (BES) model. The scales and models contained in the urban environment context include the Urban-Scale Model (UC Model), the Urban Microclimate (UMC) model using OpenFoam, and the Meteorological Meso-scale (MM model) using Climate Limited-Area Modeling (COSMO-CLM). On the database side, Revit, Global Information Systems (GIS), and building information systems (BIS) are utilized.

The coupling and co-simulation process is implemented on two case studies in Switzerland. The first case study is the ETH Zürich Hoenggerberg campus in Zürich, Switzerland. It was modeled in the CitySim simulation engine and co-simulated using work-flow automation. The target of this case study is to evaluate the differences between the coupled and solo EnergyPlus simulations based on the variables exchanged. This scenario includes the use of measured data for heating and cooling within their respective seasons to compare to the simulation results. The second case study is the EPFL campus in Lausanne, Switzerland. The objective of this scenario is to evaluate the differences between coupled and uncoupled versions of the CitySim simulation engine.

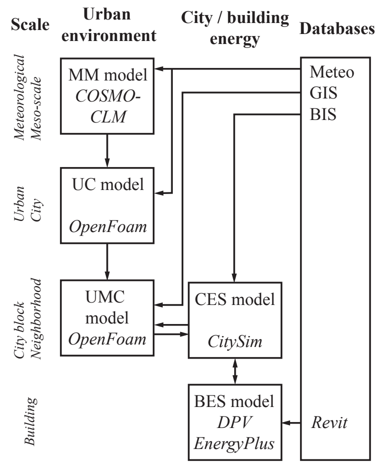

Figure 1. EnergyPlus and CitySim coupling are part of the wider context. Each block in the diagram represents an environment, with the tool/engine name in italics ((Thomas et al. 2014), adapted from (Dorer et al. 2013))

This paper describes the achievement of several objectives. The first is to automate the process of simultaneous meta-data extraction from a Building Information Model (BIM) for the creation of both building and urban-scale performance models for a real-world campus of buildings. Next, we ~~week to~~ co-simulate the urban and building scale models through concurrent information exchange. Finally, we implement a simplified calibration procedure for the first scenario by reconciling the co-simulation output results for a target building using measured energy performance data from the campus energy information system (EIS)

The first two objectives have been demonstrated in a simplified context in previous literature (Thomas and Schlueter 2012; Miller et al. 2015). The innovation in the current publication is an extension of this research through the modeling and co-simulation of real-world case studies. With respect to the third contribution, to the best of the authors' knowledge, no previous study has compared the results of a building and urban-scale co-simulation procedure to measured data from a real-world campus.

1.1. *Previous multi-scale coupling studies*

Previous attempts of information exchange have been implemented between simulation engines at various scales. Much of the initial co-simulation work in the literature is done at the subsystem and building-scale. Previous studies have analyzed strong and loose coupling of engines at this scale (Wetter 2011; Trčka, Hensen, and Wetter 2010). Coupling of building-scale simulation with urban-scale computational fluid dynamics (CFD) is attempted for modeling natural ventilation (Zhang et al. 2013) and to improve energy prediction (Bouyer, Inard, and Musy 2011). A comprehensive review of energy and airflow modeling of neighborhoods and university campuses was published that includes strategic aspects of coupling different types of models (Srebric, Heidarinejad, and Liu 2015). EnergyPlus has been coupled with ENVI- met, a micro-climate computational fluid dynamics (CFD) program (Yang et al. 2012). It was also coupled with simplified lumped parameter models to facilitate comparison with measured sensor data (Martin et al. 2015). While not directly coupled, EnergyPlus and the TEP Urban Canopy Model program were connected through a modified weather file to quantify the influences of urban localized weather effects on whole building simulation (Bueno et al. 2011)~~and urban weather generation (Bueno et al. 2013)~~.

2. Methodology

2.1. *Coupling process*

The coupling process of a simplified single zone model and contextual surrounding buildings is described in previous studies (Thomas et al. 2014), which forms the basis for the methodology in the current effort. This process utilizes the Design Performance Viewer (DPV) and associated workflow. The DPV is a tool written to extract and simulate an EnergyPlus input data file (IDF) from an Autodesk^{TM} Revit^{TM} BIM (Schlueter and Thesseling 2009). The central philosophy behind the tool is the rapid simulation of the building information model from the earliest design possible that can be used throughout the life-cycle of the building including retrofit analysis (Miller et al. 2014). This process is achieved by augmenting the information in the BIM with default values and abstracting information not relevant for energy simulation. The tool already has a simplified notion of surrounding buildings, which are modeled in the BIM as simple mass objects without further information and are exported as shading surfaces to EnergyPlus. This functionality is used for creating the CitySim mass scene and leads to a crude model of the urban context of the building. The current DPV philosophy of allowing the designer to iterate rapidly on early design decisions based on feedback about the performance of the design remains. This approach includes streamlining the process where running a simulation requires no effort from the designer due to automatic creation of input files, execution, and analysis of the results.

The coupling process of EnergyPlus and CitySim is shown in Figure 2. The solid lines depict the co-simulation of EnergyPlus and CitySim, and the dotted lines illustrate solo simulations of either EnergyPlus or CitySim. First, the DPV is used to extract an EnergyPlus simulation model from the BIM. The DPV utilizes the Revit API to extract geometrical information about the building and the physical properties of walls, windows, doors, roofs, and floors. This information is encoded in the BIM model as wall types, roof types, floor types as well as window and door families. Wherever possible, the tool uses the layering and materials of the construction types, enhancing them with physical attributes relevant to EnergyPlus. Where not defined, it assumes default values.

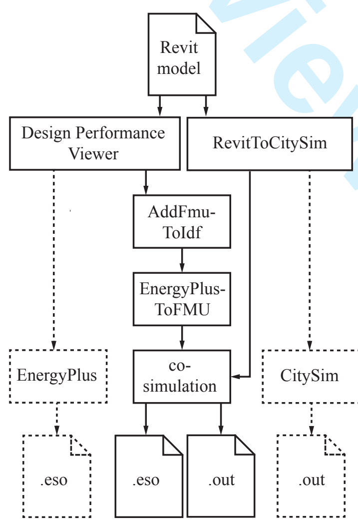

Figure 2. Overview diagram of the coupling process including tools and outputs (Thomas et al. 2014)

Next, geometry is created to be used in both the CitySim and EnergyPlus models as buildings and surfaces surrounding the building targeted in the IDF. This feature of the DPV is used for including shading surfaces in the EnergyPlus simulation model: it uses so-called *mass objects* in the BIM model as surrounding buildings. The DPV model views these buildings as a series of shading surfaces. A transformation is added to the DPV model that produces an input file for the CitySim

solver. This file uses an XML format describing the buildings in a scene for simulation, including their construction types, geometry, and systems for heating and cooling. The main BIM is extracted to the CitySim scene as one of the buildings to be simulated, with the properties of the construction types matching those in the DPV model. The glazing ratio is calculated based on the window and wall areas of the DPV model. Shading surfaces are grouped into buildings based on the mass object from which they were extracted. These adjacent buildings use default construction properties for walls and roofs, and we assign them a default glazing ratio. These defaults can be overridden by custom properties applied to the mass objects in the BIM much in the same way as the model elements of the main building are enriched with DPV information.

As of version 8.1.0, EnergyPlus supports exporting a simulation model as a Functional Mock-up Unit (FMU) (Nouidui, Wetter, and Zuo 2014). This feature introduces new IDF objects to specify the interface such an FMU exposes. These objects define which output variables are exported by the FMU and which variables are imported. The FMU export functionality is closely linked to the Energy Management System (EMS) of EnergyPlus. Co-simulation exchange variables either mimic an EnergyPlus schedule, an EMS variable or drive an EMS actuator. Since the model used by CitySim to simulate a building is more abstract than the model used by EnergyPlus, the EMS is used to aggregate certain values. CitySim does not model windows separately. Therefore, a weighted average of window and wall surface temperatures is calculated with EMS subroutines.

The FMU creation process is the basis for coupling the two models at each timestep in the simulation. Figure 3 illustrates this process from both the EnergyPlus and CitySim perspective. The augmented IDF file is fed to the *EnergyPlusToFMI* script (Nouidui and Wetter 2014). Once configured, this script produces an FMU file based on the augmented IDF file and the weather file to be used as well as a DLL file implementing the Functional Mock-up Interface that can load the IDF file, locate EnergyPlus and run the simulation.

The number of timesteps ~~per hour~~ for both CitySim and EnergyPlus is set to one per hour. The frequency of data exchanges is set to once per timestep. No data averaging over time is performed. Data exported from one simulation engine overwrites the corresponding data in the other simulation engine at each timestep. Each simulation is performed for a whole year.

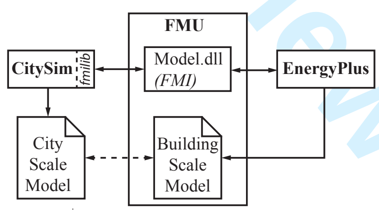

Figure 3. Simulation information exchange between CitySim and EnergyPlus using FMI (Thomas et al. 2014)

2.2. *Coupled variables*

Several key urban-scale weather variables are sent to EnergyPlus from CitySim to account better for the localized effects of surrounding buildings, geography and climate conditions. These variables are outlined in Table 1. They include various outdoor air conditions such as dry bulb and wet bulb temperatures, dew-point, humidity, wind speed and direction, and direct and diffuse solar radiation. These variables overwrite the input weather variables that EnergyPlus obtains from its weather file input. CitySim is designed to account for physical phenomenon inherent to urban environments, which are often neglected in building-scale simulation environments (Robinson and Stone 2004; Robinson et al. 2009). CitySim can be connected to a simplified micro-climate airflow model that can predict local climatic conditions around each building. Long-wave radiation exchange between the simulated building and its surroundings is sent to EnergyPlus; this process is described in detail in Section 2.3. Finally, CitySim shares its calculated occupancy schedules as it can use a deterministic or stochastic occupant behavior model, whereas EnergyPlus models are solely a deterministic models (Haldi and Robinson 2011).

Table 1. Values sent to EnergyPlus from CitySim by the FMU

Object	Variable Name	Description
Outdoor	Outdoor Drybulb	The outdoor dry-bulb temperature in °C
	Outdoor Dewpoint	The outdoor dewpoint temperature in °C
	Outdoor Relative Humidity	The outdoor relative humidity expressed in percent.
	Diffuse Solar	Diffuse horizontal irradiance in W/m^2
	Direct Solar	Beam normal irradiance in W/m^2
	Wind Speed	The outdoor wind speed in m/s
	Wind Direction	The wind direction in degrees (N=0, E=90, S=180, W=270)
Long-Wave Radiation	Environmental Radiant Temp.	Calculated T_{env} from the sky, ground, and surrounding surfaces
	Environmental Radiant Heat Gain Coefficient	Calculated h_{env} from the sky, ground, and surrounding surfaces
Zone	Occupation	Fraction of the maximum occupation (0.0-1.0) overrides the EnergyPlus occupation schedule with the CitySim stochastic schedule.

Variables sent to CitySim by EnergyPlus at each time step include several variables related to the calculation of heating and cooling loads of a targeted building. Table 2 outlines this list of exchanged variables. These variables are transferred due to the ability of EnergyPlus to model more detailed building systems, schedules, ventilation and internal load types than CitySim. For example, EnergyPlus is flexible enough to model a detailed radiant heating and cooling system that would be impossible in CiytSim. EnergyPlus is an engine optimized to accurately model building-scale systems. Thus, CitySim can take advantage of these models through coupling and co-simulation. EnergyPlus sends the heating and cooling loads, the surface temperatures of the exterior surfaces and the ventilation flow rates to CitySim.

Table 2. Values sent to CitySim from EnergyPlus by the FMU

Object	Variable Name	Description
Wall, Roof	Outside Surface Temperature	The temperature on the outside of the surface in °C
Wall	Average Outside Surface Temperature	The (weighted) average temperature of the surface on the outside in °C.
Zone	Total Heating Energy	The heating energy in Joules used in this timestep.
	Total Cooling Energy	The cooling energy in Joules used in this timestep.
	Zone Mean Air Temperature	The mean air temperature in the zone in °C
	Ventilation Volume Flow Rate	The flow rate in m^3/s (standard density)

2.3. ~~long-wave~~ Long-wave radiation exchange

~~long-wave~~ Long-wave radiation exchange in the ~~urban scale~~ urban-scale environment is coupled in the co-simulation process. It requires the development of a set of approximations to reduce the number of coupled variables between the engines and to account for differences in the methods by which each engine calculates this value. A detailed description of ~~long-wave~~ Long-wave Radiation (LWR) variable exchange and approximation is found in a previously published study (Miller et al. 2015) on a simplified theoretical case.

In EnergyPlus, LWR exchange for a surface is calculated through the summation of radiation gain from the ground, sky, and air as seen in Equation 1 and Figure 4a (United States Department of Energy (DOE) 2015). The radiant heat transfer coefficient for each of these environmental variables is calculated according to Equation 2 with σ as the Stefan-Boltzmann constant, ϵ as the emissivity and $F_{variable}$ being the view factor to the variable that can be sky, grd (ground) or air. A major assumption of this approach is that the modeled building's surfaces and those of adjacent buildings are at a uniform temperature and the LWR radiation exchange is negligible; a situation that is an

oversimplification in an urban scale domain (Evins, Dorer, and Carmeliet 2014).

$$Q_{LWR,EnergyPlus} = h_{r,grd}(T_{surf} - T_{grd}) + h_{r,sky}(T_{surf} - T_{sky}) + h_{r,air}(T_{surf} - T_{air}) \tag{1}$$

$$h_{r,variable} = \frac{\epsilon\sigma F_{variable}(T_{surf}^4 - T_{variable}^4)}{T_{surf} - T_{variable}} \tag{2}$$

In comparison, CitySim calculates LWR exchange by calculating an aggregated equivalent temperature, T_{env}, and radiative heat transfer coefficient, $h_{r,env}$, from surrounding urban surfaces in addition to ground, sky, and air (Robinson et al. 2009). The calculation for T_{env} is expressed in Equation 3 with the F values being view factors of the surrounding environment including adjacent surfaces $i = 1..n$. $h_{r,env}$ is based on a first order Talyor development of the numerator of Equation 2 around $(T_{surf} + T_{variable})/2$ and therefore $Q_{LWR,CitySim}$ is calculated using Equation 4.

$$\sigma T_{env}^4 = \sigma F_{sky} T_{sky}^4 + \sigma F_{grd} T_{grd}^4 + \sum_{i=1}^{n} \epsilon_i \sigma F_i T_i^4 \tag{3}$$

$$Q_{LWR,CitySim} = h_{r,env}(T_{surf} - T_{env}) \tag{4}$$

In the coupled simulation, EnergyPlus uses the CitySim supplied equivalent $h_{r,env}$ and T_{env} to calculate weighted $h_{r,sky}$, $h_{r,grd}$, and $h_{r,air}$ values using the view factors and the sky-to-air split ratio. Figure 4 illustrates the schematic differences between the solo and coupled simulations on a theoretical example of a target building with two adjacent buildings with surfaces available for radiation exchange.

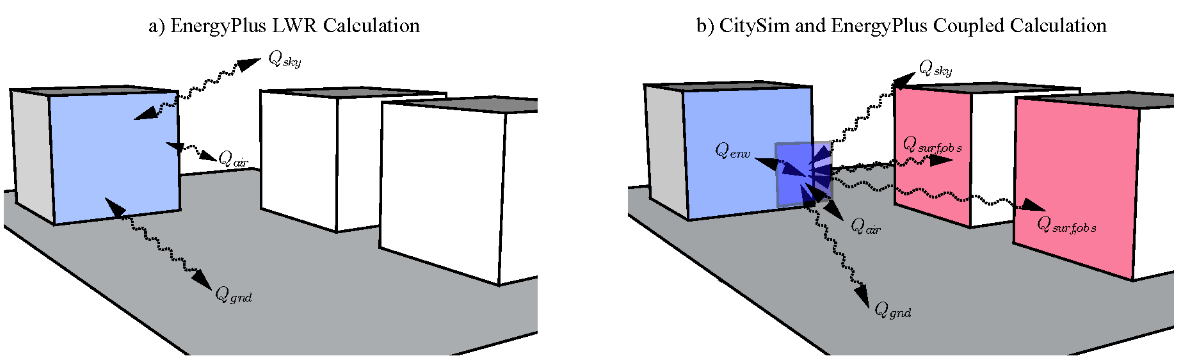

Figure 4. Comparison of the LWR components between a) Solo EnergyPlus and b) Coupled CitySim/EnergyPlus configuration (Miller et al. 2015)

2.4. *Work flow automation*

The coupling, simulation and co-simulation process is completely managed within a program called VisTrails (Freire et al. 2014). The implementation of this type of workflow is outlined in previous work focused on automating DPV using the Kepler platform (Thomas and Schlueter 2012). This process reduces the effort expended by a designer down to pressing a single button. This functionality allows an iterative design informed by readily available simulation results. An automated workflow ties the various steps together and maintains the effortless iterative design process. VisTrails enables the coupling of various workflow subprocesses script initializations, executions of the engines, and

the compilation of the outputs. This tool empowers the coupling of multiple executable files and their connecting scripts in graphical diagrams that enhance reproducibility and process automation (Freire et al. 2014). The VisTrails workflow diagram for the first case study in this paper is seen in Figure 5.

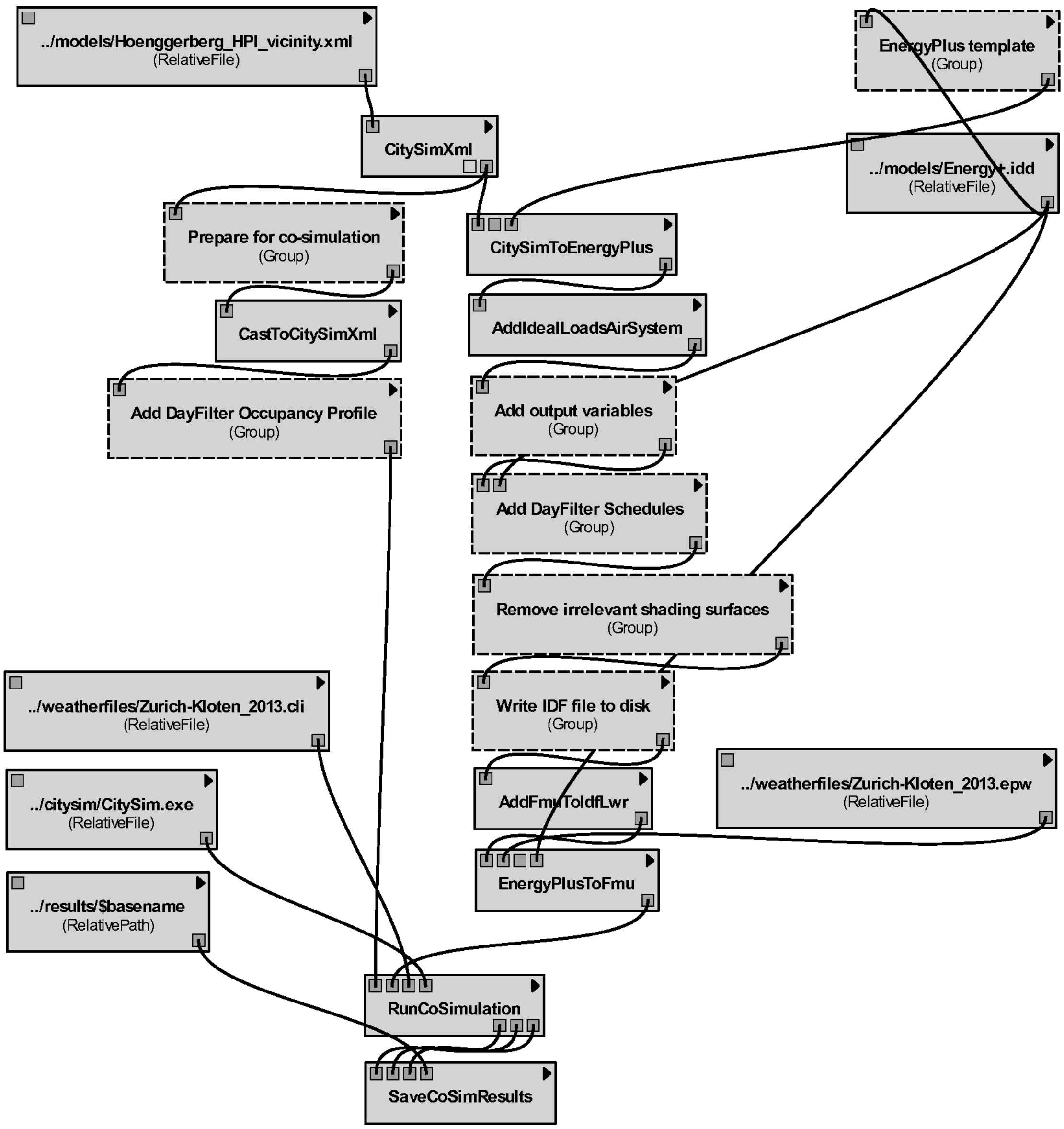

Figure 5. Workflow in VizTrails

2.5. *Simplified calibration*

In the first case study, one aspect of this analysis is the comparison of the actual measured performance of the target building on campus with the ~~simulation~~ results of the co-simulation. A simplified calibration procedure is adapted from previous research to compare the measured heating and cooling data available on campus with various simulation scenarios (Samuelson, Ghorayshi, and Reinhart 2015). This calibration procedure was utilized in the performance reconciliation of 18 buildings that were built according to the LEED Canada protocol and were under review of ~~actualized~~ actual performance. This protocol is unique in its analysis process to uncover design model deficiencies in a step-wise manner, utilizing the most readily available knowledge first and working towards equilibrium between ~~measured and simulated~~measurement and simulation. There is an appropriate balance between the effort of implementation and value generated through the calibration process.

3. Implementation

The co-simulation process is implemented on two case studies in Switzerland. The first is the ETH Zürich Hoenggerberg campus in Zürich, Switzerland. The focus of this case study is to quantify the impact of the information exchange through co-simulation within the EnergyPlus engine. The intent on this campus was to develop techniques for retrofit analysis using EnergyPlus. The targeted building on this campus is the HPI Building. Raw measured data is available for many of the buildings on campus, thus a simplified calibration procedure is used to reconcile the simulation results.

The second case study is the EPFL campus in Lausanne, Switzerland. The targeted building, in this instance, was the Quartier Nord complex. The focus of this study was to compare the solo and co-simulation output results of CitySim. Reliable measured data for calibration is not currently available for this building.

3.1. *Campus case study 1: ETHZ Hoenggerberg Campus*

The ETH Zürich Hoenggerberg campus includes 32 higher education facilities with spaces allocated to laboratories, office space, lecture halls, cafeterias, data centers and other types of similar areas. The campus has a centralized energy management system (EMS) that contains 807 energy and water measurement points from heating, cooling, electricity, city gas, domestic hot water, gray water, and general water consumption.

The focus of the co-simulation process is that the performance of a targeted building is evaluated through solo and coupled methods. The HPI building on campus was chosen in this case study due to the amount and quality of measured data available from the EMS for this building. HPI is a 2,610 square meter building that is made up mostly of office space and classrooms. It also includes 400 m^2 convenience store and coffee shop. The building is indicated on a campus map shown in Figure 6 and is shaded red.

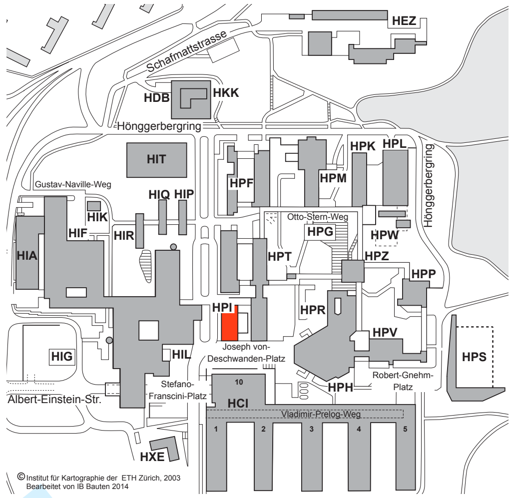

Figure 6. ETH Hoenggerberg campus map with the HPI building shaded red

3.2. *Model development*

In order to perform a co-simulation of the targeted buildings, initially a CitySim model of the campus was developed. Through the workflow automation process, this geometry was converted into an EnergyPlus input file as seen in Figure 7. The EnergyPlus input file was then used as an input to execute EnergyPlus solo and co-simulation processes for the purpose of simplified calibration, and then to understand the magnitude of the difference between these simulation scenarios.

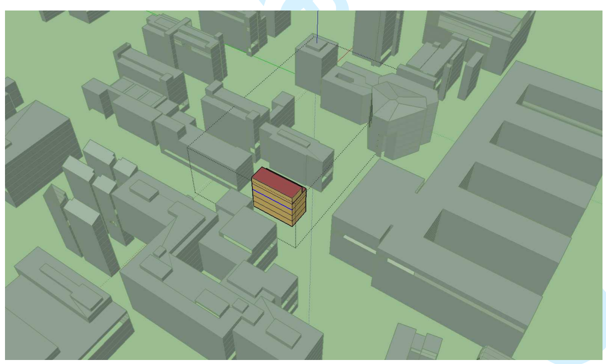

Figure 7. The HPI building EnergyPlus model extracted from the CitySim model. The HPI building is seen as the light and dark brown building in the center surrounded by gray masses that represent other buildings on campus. The graphic is illustrated with OpenStudio for Sketch-up.

3.3. *Measured data collection and calibration*

Energy data from the HPI building was collected and analyzed in the context of the simplified calibration procedures. The measured datasets were screened and aggregated into typical usage profiles to be used for the lighting, ~~plug-~~ plug loads, and HVAC equipment availability schedules and power densities. Figure 8 illustrates the aggregation examples of electrical energy for the HPI building. This profile was created through a filtering and clustering process known as *DayFilter* (Miller, Nagy, and Schlueter 2015). Cluster 0 represents the typical energy profile for Sunday, while Cluster 1 dominates the Saturdays of the data set. Clusters 2 and 3 make up most of the weekdays of the data set with Cluster 3 being more common in non-summer months. These profiles are used to set the availability schedules as inputs into the EnergyPlus simulation to emulate the way occupants inhabit the building and how the building management system (BMS) controls the lighting and HVAC systems.

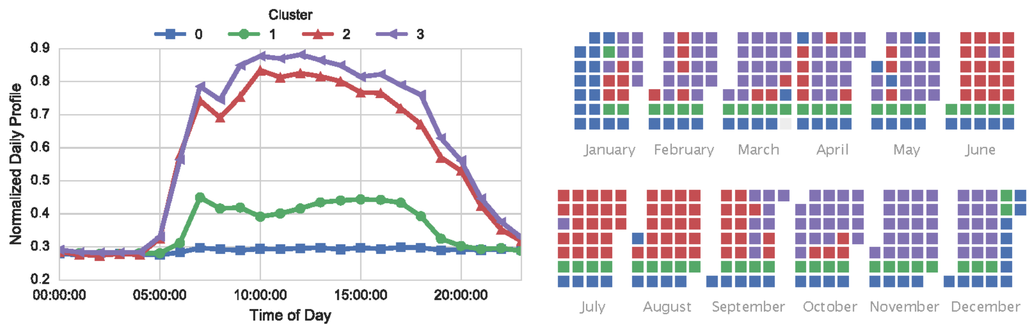

Figure 8. Typical measured data electricity profiles of (left) average daily electrical consumption for each cluster and (right) color-coded calendar of which days fall within each cluster. The diagram on the right is each month of the year with each row corresponding with a day of the week (starting with Monday) and each column corresponding to a week of the month.

The measured and simulated data from both the co-simulation and EnergyPlus solo simulation were analyzed in order to understand how both the solo and co-simulations compare to real, measured data. The calibration process was undertaken through a series of steps such as including local weather conditions for the simulation period and adding custom lighting schedules and power densities extracted from the measured data. The models were calibrated to the summer season (May-September) for cooling and the winter season (Jan-April and October to December) for heating. Figure 9 illustrates a comparison of the measured data with the simulations after the tuning process. The final calibrated EnergyPlus solo model had a normalized mean bias error (NMBE) of -9.36% and a coefficient of variation of root mean square error (CVRMSE) of 21.7% for cooling and 5.02% and 29.4% for heating. These metrics fall within the +/-10% NMBE and +/-30% CVRSME used in this case study for calibration. A total of 37 calibration iterations were undertaken to modulate the simulation results to within these criteria. The goal of calibration, in this case, is to just bring the models to within a reasonable range of reality in order to bring more confidence to analysis of the discrepancies between the solo and co-simulation scenarios.

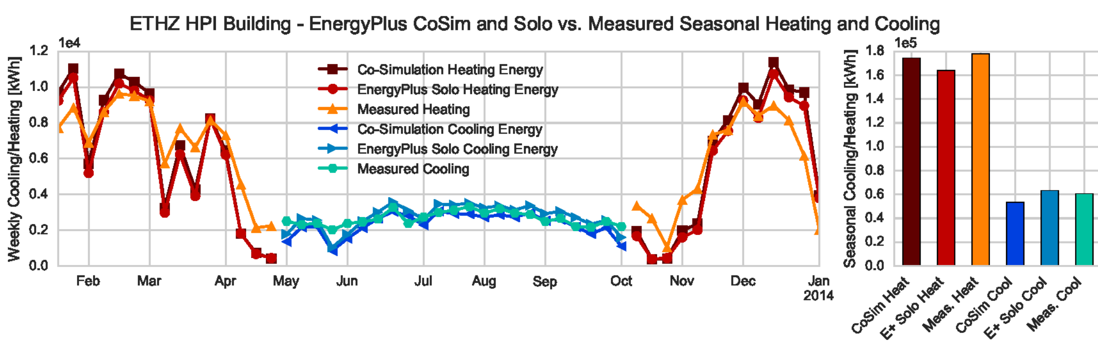

Figure 9. HPI Measured vs. Co-Simulation and EnergyPlus Solo for Heating and Cooling Seasons

3.4. *EnergyPlus co-simulation results*

For cooling, a discrepancy can be seen between ~~co- simulation~~ co-simulation and solo EnergyPlus. Co-simulation decreases the predicted cooling energy by 15.5%, as seen in Figure 10. Figure 11 illustrates the difference in predicted heating energy consumption across the test year. A consistent offset exists across the time frame of days in January, the peak of the heating season. A more varied discrepancy across the heating months is noticed resulting an overall increase of heating prediction of 6.5% due to co-simulation. The exchange of long-wave radiation for this particular site is substantial due to the proximity of surrounding buildings.

When comparing the solo and co-simulated models to the measured data, it is noticed that cooling energy is over-predicted by the solo simulation by 4%, while co-simulation under-predicted by 11.1%. This discrepancy is likely due to a loss in long-wave radiation in the co-simulation to the surrounding buildings, thus reducing the overall cooling load.

For heating energy, co-simulation was able to bring the predicted value to within 2% of the measured value for the year, an improvement as compared to the solo simulation, which was 8.5% less than the measured value. This situation is also likely due to the long-wave radiation loss to surrounding buildings, thus increasing the overall heating load.

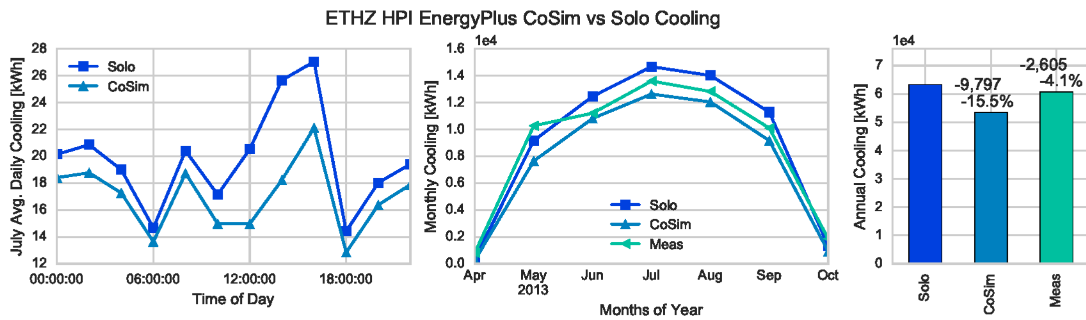

Figure 10. HPI Co-Simulation vs. EnergyPlus Solo for Cooling

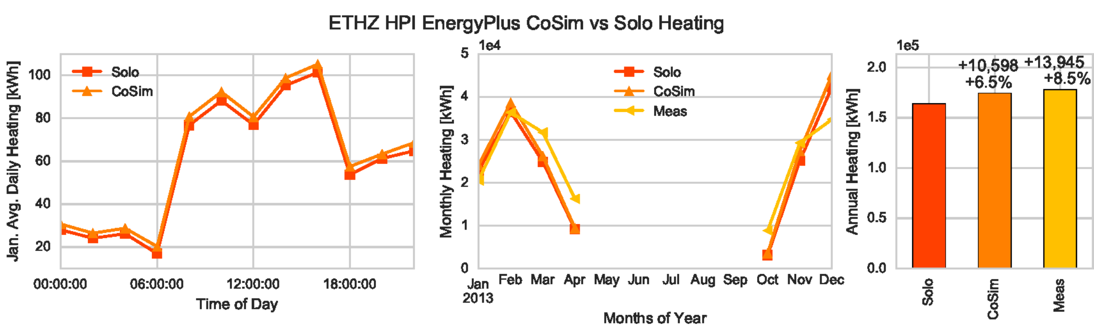

Figure 11. HPI Co-Simulation vs. EnergyPlus Solo for Heating

3.5. *Campus case study 2: EPFL Quartier Nord*

Quartier Nord is a whole new quarter of the École Polytechnique Fédérale de Lausanne (EPFL) campus located at its northwest corner. This complex includes a Convention Centre with an auditorium with a maximum capacity of 3000 (seated) people, housing for 516 students, retail and service areas and a hotel. As a public space, this ensemble is organized around the central plaza as seen in Figure 12). With a particularly strong visual and formal identity, the SwissTech Convention Centre (STCC) is clearly the key protagonist. Designed as a Minergie building, it includes modern energy conversion technologies to reduce its energy consumption (Beyeler, Beglinger, and Roder 2009). The focus of the co-simulation is realized on the STCC, simulated with the nearby buildings for housing, retail and service areas~~(Beyeler, Beglinger, and Roder 2009)~~.

Figure 12. The Quartier Nord at EPFL in Lausanne

3.6. *Model development*

The information required in the simulation mainly comprises three parts: physical, geometrical and operational data. The geometry information including the shape, dimension, structure and materials was obtained from the Real Estate and Infrastructure Department of École Polytechnique Fédérale de Lausanne (EPFL), which was responsible for carrying out the project from call to tender to construction. However, since the documents provided were conflicting with what has been installed, the task to realize a precise model of the buildings itself is rather tedious. Besides, it is even more challenging to get the operational data (daily occupancy, lighting, and electrical equipment usage level and ventilation rate) as the building has only recently been set in operation mode and as engineers and technicians have been working on improving the controls. Therefore, due to unreliable monitoring data, the calibration step of the model was not undertaken.

Considering the lack of detailed information about the building, a so-called detailed reference case was modeled with EnergyPlus (Mauree et al. 2015) in which regulation standards applied in the design phase from the local building code norms were used to complete the missing information. A rendering of this model is seen in Figure 13.

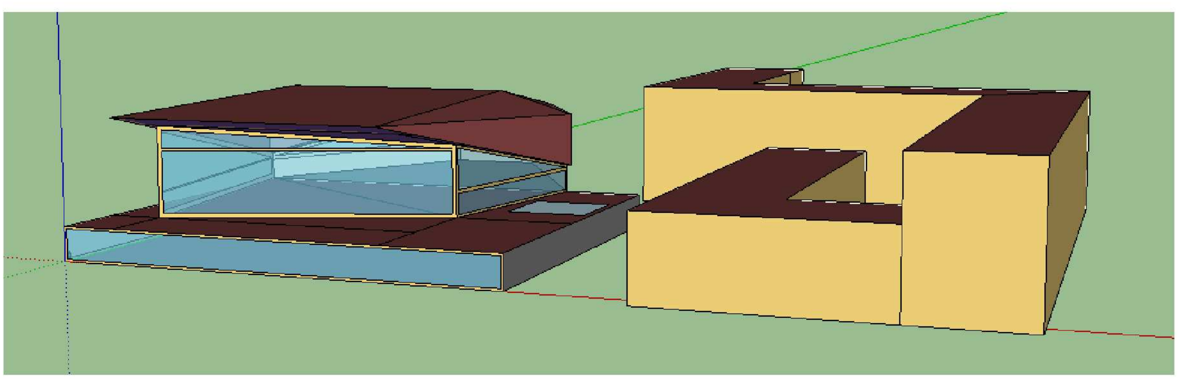

Figure 13. The Quartier Nord modeled with OpenStudio for Sketchup[2]. The STCC on the left is the main focus of the study and is represented by two thermal zones.

The corresponding CitySim model was created by exporting a DXF file from EnergyPlus for the whole of Quartier Nord, and importing it into the Graphical User Interface of CitySim. Physical characteristics of the building were added to complete the CitySim model. Finally, the same script as described in Section 2 was used to export the model from CitySim to EnergyPlus, giving a simplified EnergyPlus model.

3.7. *Comparison of EnergyPlus and CitySim*

Both the CitySim and EnergyPlus engines are utilized in this case study. The first comparison to observe is the differences between the two engines when focused on the STCC building. When simulated in isolation, the CitySim engine predicts a 28.6% increase in heating load and a 44.4% increase in cooling load as compared to EnergyPlus. This phenomenon is due to the differences in the way each of these engines calculates heating and cooling loads. CitySim has a much more simplified model of building occupants, lighting, and plug loads. CitySim also includes long-wave radiation exchange calculations that can greatly influence the heating and cooling load calculations as well. Use of the co-simulation process brings the engines to within 5.4%. Figure 14 illustrates these differences for cooling and Figure 15 for heating.

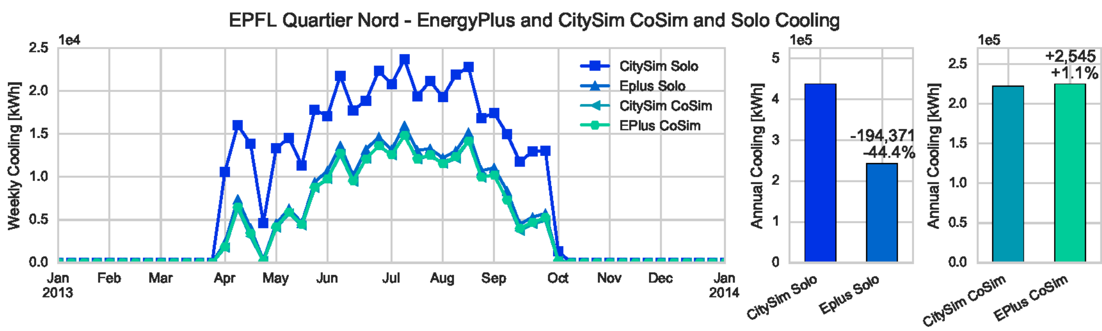

Figure 14. STCC CitySim vs. EnergyPlus Solo for Cooling

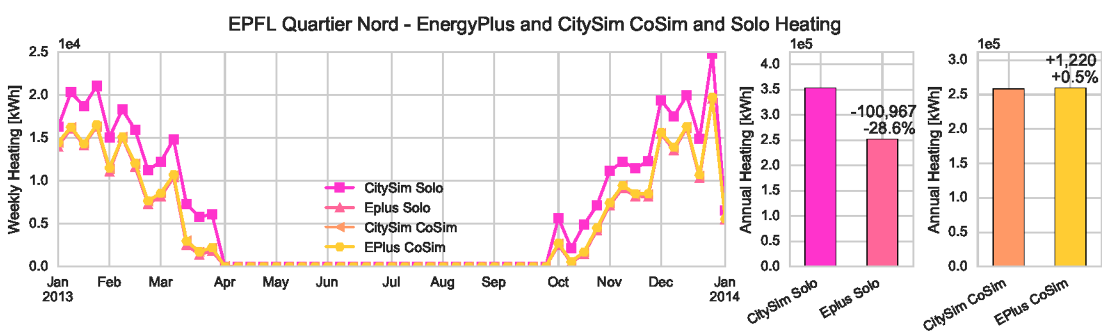

Figure 15. STCC CitySim vs. EnergyPlus Solo for Heating

3.8. *EnergyPlus co-simulation results*

The STCC building is also simulated within the solo and co-simulation environments. When focusing on the EnergyPlus results, a 7.5% decrease in cooling energy is observed, as seen in Figure 16. A 2.8% increase in heating energy is observed, as seen in Figure 17. These differences are less pronounced than the HPI and theoretical case studies due to the number and proximity of surrounding buildings is not as large. long-wave radiation exchange in this situation doesn't have as large of an impact on the heating and cooling calculations.

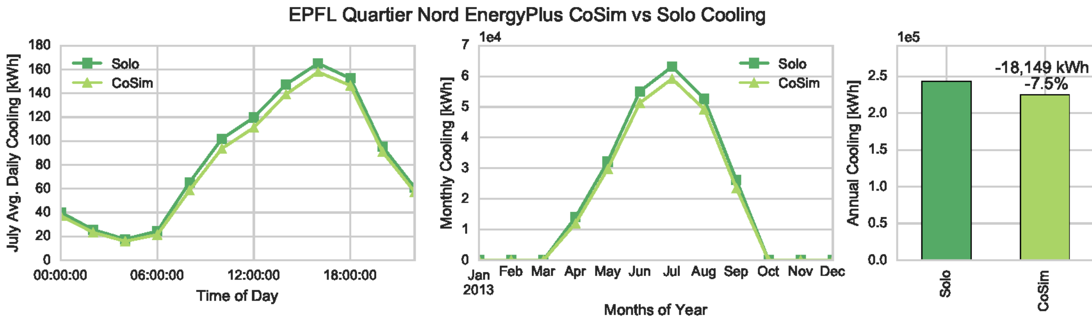

Figure 16. Quartier Nord EnergyPlus Co-Simulation vs. Solo for Cooling

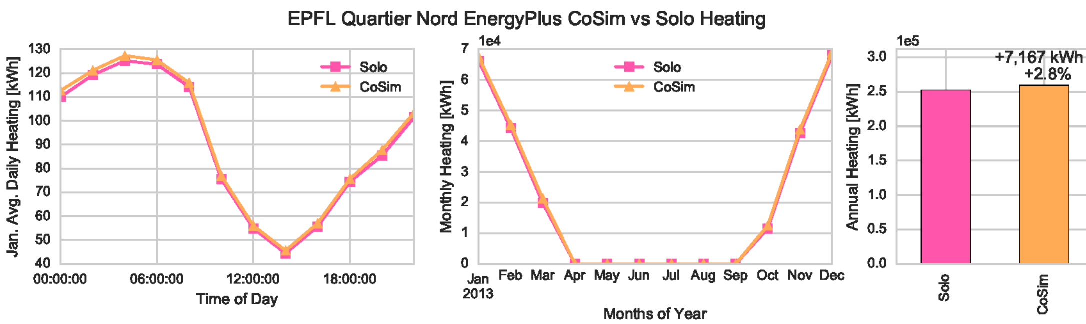

Figure 17. Quartier Nord EnergyPlus Co-Simulation vs. Solo for Heating

4. Discussion

Two campus case studies were presented in this paper to showcase a unique process of extracting model meta-data, conversion of those data into input files for two separate simulation engines, and the solo and co-simulation process of those engines~~on two real-world case studies~~. The analysis of the results shows that for the first case study, co-simulation can achieve values closer to measured reality for heating, but not cooling. These results are unique to this case study and simply show that the co-simulation process may be helpful for heating only~~in this particular instance~~. A limitation of this study is that we only analyze a single building against measured data in this context. In the second case study, significant discrepancies are found between the CitySim and EnergyPlus engines which were corrected using the co-simulation process.

One of the key insights in this work is that each of the engines is enabled to account for the various physical phenomenon in their simulation process that were previously impossible. For example, through co-simulation, EnergyPlus was able to utilize the long-wave radiation exchange capabilities of CitySim. The ability to couple and leverage the best aspects of multiple simulation engines can enhance the modeling of large-scale urban agglomerations.

Disadvantages of the co-simulation process are mainly centered upon the increase in computing time and power needed for the FMI to coordinate data exchange between the two simulation engines. After calibration, a comparison of the run-times of the co-simulation and solo EnergyPlus simulations show that the execution time for the solo EnergyPlus simulation was 1 minute and 49 seconds compared to 28 minutes and 10 seconds for the co-simulation.

5. Conclusion

This paper outlines the implementation of a fully automated ~~workflow~~ work flow process that extracts geometry information at the urban-scale, creates the necessary input information, executes each engine with information exchange at each time step of targeted variables, and accumulates the results of the analysis. The process has been implemented on simplified theoretical scenarios in the past, and the key innovation with this work is in implementation on actual ~~case study~~ case-study campuses and targeted buildings. The results illustrate that the differences between the ~~co- simulation~~ co-simulation and solo environments are within range of previous theoretical models. More reliable results of the magnitude of differences between the simulation techniques can be extracted from these real-world scenarios.

Future work in using co-simulation models for buildings and campuses would more intensively utilize the model results in a practical implementation of retrofit scenarios or urban-scale energy systems research. More implementations would also test the feasibility of using co-simulation for ~~retrofit~~ systems analysis, urban planning studies, and cooling and heating system optimization.

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Review Comment Responses to Journal of Building Performance Simulation Submission

Paper Title: Urban and building multiscale co-simulation: case study implementations on two university campuses

June 9, 2017

1 Review 1

1.1 General comments from reviewer

This is a valuable paper that pinpoints the differences in estimated energy consumption between simulations of solo building and buildings modeled in an urban context. The paper relies on am emerging simulation workflow and extends its application to two real-building scenarios. Work by the authors and others is amply referenced; together the text and the references provide excellent explanation of the linkages between building and city simulations.

The paper can be improved in a large number of small ways, as indicated in specific comments. In particular, the central figures. 10, 11, 14 and 15 and accompanying text need attention to improve clarity and correct inconsistencies between text and images. The suggested improvements should be straightforward.

1.2 Response to general comments

Thank you for the comments on the importance and value of the paper and we welcome the comments and feedback to be covered in this review.

1.3 Revision items

a) 1. p. 1. Abstract. The abstract quantifies percentage impacts of co-simulation of heating and cooling consumption but does not establish a reference: percentage change relative to what base case? The abstract promises a discussion of strengths and weaknesses of the developed process but the paper does not include a discussion section and the conclusion does not summarize strengths and weaknesses.

The abstract has been updated to reflect that the baseline of these comparison metrics are the EnergyPlus solo simulations of each of the engines.

A discussion section has been added to address the strengths and weaknesses mentioned in the abstract – advantages are related to the enhancement of each of the engines and disadvantages related to the increase in computing power needed to undertake the process.

b) 2. p. 1. Introduction. Lines 3-5 state that 2.5 billion people are expected to join cities throughout the world. What is the associated time frame i.e., by what year?

The United Nations World Urbanization prospectus projected that figure by 2050 – this fact has been updated in the introduction

c) 3. p. 1, line 13. Please consider a lower-case S for solver.

Lower-case "S" has been used.

d) 4. p. 1, lines 21-23. The text states that a single equation approximates the total mass flow rate required to meet the sensible and later loads of each building. In this reviewers experience, there are separate mass-conservation equations for air and water vapor as well as an energy-balance equation. Perhaps the authors could succinctly amplify their statement.

This observation is correct – "The heating, ventilation, and air-conditioning (HVAC) systems are modeled using a single equation set of equations that approximates the total mass flow rate required to meet the sensible and latent loads of each building as a whole." is a mis-statement. This sentence has been changed to a "set of equations"

e) 5. p. 2, line 40. Please replace phenomenon with the plural phenomena.

Correction made.

f) 6. p. 2, line 60. The text appears to limit the second case study to CitySim simulation output but the abstract and, later, line 224, include analysis of EnergyPlus output.

The reference to the EnergyPlus simulation for this case study was removed.

g) 7. p. 3. Figure 1 includes acronyms not defined in the text or caption.

Explanation of the acronyms is now included in the text.

h) 8. p. 3, lines 62-68. For grammatical consistency, the achievements should all start with verbs (automate, co-simulate, implement) or nouns (automation, co-simulation, implementation). The third achievement should specify what simulation model is being calibrated.

Points were revised to all be verbs and the second scenario was indicated as the model being calibrated.

i) 9. p. 3, lines 88-89. Please note that Bueno et al. 2013 generated urban weather with a nodal model and did not directly couple EnergyPlus to a nodal representation of the urban canopy layer. The accuracy of this approach depends on how faithfully users and the model represent the buildings that will later be simulated in detail in EnergyPlus with the modified weather file.

It was noted that this study doesn't directly couple the simulation engines, but only connects them through a modified weather file.

j) 10. p. 4, line 97. Please consider earliest design possible and it can be used or earliest design possible that can be used.

Change made to the latter suggestion

k) 11. p. 4, Figure 2. The test explains the paths associated with the dotted vertical lines and solid lines. Presumably the use of the latter is intended to show the co-simulation path but the use of the dashed line in the related Figure 3 is not clear. Further, Figure 3 is quite small; at minimum, the CItySIm block with its italicized vertical text, fmilib, could be modestly larger.

It is correct that the dotted line is meant to show the co-simulation path in Figure 2. Therefore the dotted lines have been removed from Figure 3 for consistency sake and the text has been modified to be more readable.

l) 12. p. 5, lines 145-154. The text states that several key urban-scale weather variables are send to EnergyPlus from CitySim but does not succinctly state how CItySIm calculates these variables. The text might indicate why the authors consider the CitySim occupancy model to be more robust. Finally, as a minor point of English grammar, please consider removing the comma after urban environments in line 150 or replacing that with which.

The next now explains how CitySim has simplified micro-climate airflow model that can predict local climatic conditions around each building. It also further describes how CitySim shares its calculated occupancy schedules as it can use a deterministic or stochastic occupant behavior model, whereas EnergyPlus models are solely a deterministic models. Grammar changes have been noted.

m) 13. p. 6. The text on this page (or, apparently, any other) does not refer to Tables 1 and 2.

References for Table 1 and 2 are now included in the text pertaining to those variables.

n) 14. p. 7, line 178. Equation 2 lacks a view factor, as is included in Evins et al., Equation 9 and in the EnergyPlus Engineering Reference.

That is correct – a view factor has been added to Equation 2.

o) 15. p. 7, lines 195-196. The sentence beginning with An automated workflow lacks a verb. Please consider replacing to tie with ties.

Correction made.

p) 16. p. 9, line 215. Please consider replacing compare with quantify, given that the sentence does not establish the basis of comparison (compare what with what)).

Correction made.

q) 17. p. 10. Section 3.2. The text states that the campus geometry was converted into an EnergyPlus input file as seen in Figure 7. However, this figure does not clearly indicate what geometry was included in the IDF and the caption states that the HPI building was modeled in Open Studio.

The caption for Figure 7 has been updated to clarify the situation in which the HPI building was extracted from the CiytSim model, however it is illustrated using OpenStudio due to that software's rendering capabilities. The caption also clearly states which building is being simulationed.

r) 18. p. 10, lines 246-248. Please consider replacing are screened with were screened and removing the hyphen after plug.

Correction made.

s) 19. p. 10, section 3.3. Either the text (lines 245-252) or the caption for Figure 8 should say a bit more (a sentence would be adequate) about the clustering process. For example, the caption could note that the rows for each month refer to days of the week (if this is true) and could name (describe) each of the clusters (i.e., clusters that nominally align with weekdays, Saturdays and Sundays/school holidays).

The caption for Figure 8 was revised significantly to describe what the reader is seeing in the typical average profiles on the left and the days corresponding with each cluster on the right. Text was added in the preceding paragraphs that briefly describe the significance of each of the clusters.

t) 20. p. 10., lines 253-259. Please rewrite the sentence to avoid compared to create scenario for comparison. What is meant by measurements were deemed most accurate during the appropriate seasons?

The first sentence of that paragraph was rewritten to avoid the use of ”comared” and ”create a scenario for comparison”. The sentence pertaining to the seasonal nature of the data analysis was removed as it didn’t add any information to the fact that only heating and cooling seasonal data was used for each calibration.

u) 21. p. 11, lines 261-262. The NMBE for heating and cooling are exactly the same and the NMBE for cooling is not in accord with the bar charts in Figure 9.

The NMBE for heating is actually 5.02, thus the repetition of the -9.36 value is a type. This has been corrected in the text.

v) 22. p. 11, section 3.4. Please see the following comments for the two associated figures. In addition, the presentation of results from the study of Miller et al. is not clear. Does the Miller study compare solo and co-simulation results? If so, which results are the reference for the percentage changes? Should the reader conclude that the differences between Miller and this study are comparable (which is comforting) or that deviations are significant, in which case they should be explained.

The Miller study does compare solo and co-simulation results, but in an entirely different context. It is difficult to compare the difference between the two sets of simulations as the buildings tested are different, thus, the discrepancies between co-simulation and solo could be wildly different or very similar either one. Due to this, reference to this study and its comparison to the results of the campus co-simulation have been removed.

w) 24. p. 12, Figure 11. The text states Figure 11 shows differences in predicted heating consumption and notes there is a consistent offset across days in January. Figure 11 shows hourly variations for presumably averaged days and single points for each month; in short, variations across days cannot be discerned. Are these variations important to the comparison? The order of the bars matches Figure 10 but disagrees with Figure 9. The text compares co-simulation with measurement (using the latter as the reference, which seems appropriate) and shows 2% annual difference but the numbers over the bars appear to compare co-simulation and measurement with solo simulation and show 6.5% difference. As in Figure 11, the numbers (not percentages) over the bars are not explained.

For Figure 11, we believe the variations are important to show at the daily, monthly and annual levels because even if they have small offsets and little variation at those scales, that information itself is insightful. For example in the monthly chart, March and April have a larger offset than Jan and Feb for heating. The order of the bars in all of the charts has been made consistent. The measured data has been made the baseline for the percentages, thus making it more clear how the solo and co-simulation perform as compared to the measured data.

x) 25. p. 12, section 3.5. The text should include a reference to the Minergie standard and the caption or image in Figure 12 should identify the STCC building.

Minergie Standard added.

y) 26. p. 13, line 308. Please explain SIA and/or provide an appropriate reference.

The term SIA was replaced with local energy code standard.

z) 27. p. 13, lines 310-313. The text states that the CItySIm model was created from a DXF file from EnergyPlus. Was this export used solely for the STCC building or was the remainder of the Quartier Nord as shown in Figure 13 designed in Open Studio?

No, the export from EnergyPlus included both buildings – this fact has been clarified in the text.

) 28. P. 13, lines 316-322. The reference in the text for percentage changes is the EnergyPlus simulation but Figures 14 and 15 place the percentages (with opposite sign) about the solo simulations. The text states that discrepancies between solo and co-simulations are due to differences in calculation of heating and cooling loads. Please elaborate.

An explation of how the different engines calculate heating and cooling loads was added.

) 29. P. 14, section 3.8. The text states that the Quartier Nord building was also simulated. This is a bit confusing because Quartier Nord previously referred to the complex. Does the building refer to the building on the right in Figures 12 and 13 i.e., everything except the STCC? The text also states that differences between solo and co-simulations are small because the surroundings are sparse. If this is the case, would one expect better agreement between solo and co-simulations for the neighboring STCC? Also, please consider replacing due to with because in line 327.

It is not the 'Quartier Nord Building' that is being simulated – it is the STCC. The text has been fixed to clarify this confusion.

) 30. p. 15. Conclusion. There is no summary of strengths and weakness of the process presented in the paper and the future work is limited only to more practical implementation. Is there nothing to improve?

A discussion section was added with advantages and disadvantages as well as future research directions.

) 31. p. 16. The first and last references, by Miller et al. and Zhang et al., lack volume and page numbers. Throughout the reference section, the authors should consider consistency in use of initials versus given names.

References are updated based on the feedback.

2 Review 2

2.1 General comments from reviewer

This is a nice study in a series of studies that use institutional buildings for demonstration of different co-simulation strategies for modeling of urban environments and building energy consumption. Here are several review comments that are mostly focused on the fact that actual execution of co-simulation was not discussed in details; the study mostly presented the co-simulation workflow and results.

2.2 Response to general comments

Thank you for taking time to perform this review and for the in-depth comments related to discussing the execution of the actual co-simulation.

2.3 Revision items

) (1) At the top of page 2, the paper describes advantages of EnergyPlus. However, it is not clear why this simulation engine is used when several others could perform the presented analyses. It is important to know what technical aspects of the co-simulation procedure specifically drove the authors to use EnergyPlus.

It wasn't necessarily the technical aspects of EnergyPlus that were the basis for choosing it in this study. The more relevant factor for us was familiarity and knowledge of using the engine and its ability to use FMI to interface with another program. Content has been added to emphasize these points.

) (2) The actual co-simulation, which is the main contribution of this study is not well discussed. Specifically, the paper needs to describe: (a) frequency of data exchanges, (b) whether any data averaging took place, (c) whether the numerical scheme is stable and grid independent, (d) what is the time step for each engine?, (e) what is the simulation time?, (f) are these annual, monthly, or daily simulations?, (g) what convergence criterion was used?

Content was added in this section which touches upon each of these points.

) (3) Figure 3, Section 2.3, and Figure 4 are the same or similar to authors previous publication. A citation would be sufficient.

We chose to replicate these figures in this publication to clarify the bigger picture of the scope of the study. We believe these figures help to put the current study in context in a better way.

) (4) In Section 3.3, the paper needs many more details on the calibration process, including the specification of all calibration steps undertaken, rather than just cursory listing some of the steps.

A total of 37 calibration steps were undertaken to tune the model – it would be extremely tedious and lengthy to specify each of these steps and their modivations in the calibration process, especially since the goal is simplified calibration. Content has been added about the number of iteration steps and their impact on the calibration process.

) (5) Please, discuss results in Figure 10. What are the numerical or physical reasons for the solo case to underperform?

Figure 10-17 have content added to help further explain discrepancies and significant content has been added in the new Discussion section into why these discrepancies are relevant.

) (6) The conclusions need content on co-simulation execution challenges and how they were overcome during the course of that this study.

The new Discussion section now also details the challenges, advantages and disadvantages of the study.

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Research Article

Urban and building multiscale co-simulation: case study implementations on two university campuses

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The co-simulation of both urban and building-level models leverages the advantages of both platforms. It better accounts for the localized effects of surrounding buildings, geography and climate conditions while maintaining high-fidelity building systems representation. This paper describes the co-simulation process of the building and urban scale models of two university campuses in Switzerland using EnergyPlus and CitySim. In the first case study, on-site measured performance data is compared to the co-simulation results. The second case study examines the results of the two engines. The results show that coupling of EnergyPlus with CitySim resulted in a -15.5% and -7.5% impact on cooling consumption and a +6.5% and +4.8% impact on heating use as compared to solo simulations.The co-simulation process was able to better model realistic conditions for heating, but not cooling in one case study. It was able to substantially reduce the discrepancies in prediction between the engines in the other study.

Keywords: Building-scale simulation, Calibrated energy models, CitySim, Co-simulation, EnergyPlus, Urban-scale simulation

1. Introduction

Urban scale building performance simulation is a process that empowers the analysis and optimization of cities. Urban populations are growing around the world at an unprecedented rate. A transition from urban to rural is underway and 2.5 billion people are expected to join cities throughout the world by the year 2050 (United Nations 2014). Expansions of entire districts and even cities is not an uncommon phenomenon, especially in East Asia and Africa. Urban scale modeling is in the midst of an intense focus on the research community with six key areas of practice: technology design, building design, urban climate, systems design, policy assessment, and land use and transportation (Keirstead, Jennings, and Sivakumar 2012). The ability to simulate the interaction between large collections of buildings enables the development and testing of optimization and planning scenarios for this new development (Dorer et al. 2013).

The CitySim simulation engine is an example of such a program designed and optimized for urban-scale simulation. CitySim is an urban performance simulation engine that comprises a solver module as well as a graphical user interface. It focuses on the energy flows of multiple simplified building models and their interdependent relationship with their urban climate (Robinson et al. 2009). CitySim includes building thermal, urban radiation, occupant behavior, and plant/equipment models integrated as a single simulation engine. CitySim simulates multiple buildings up to city scale using simplified models to achieve a good compromise between modeling accuracy, computational overheads, and data availability. Each building's thermal behavior is based on an electrical analogy using a two node resistor- capacitor network. The internal lighting, people, and miscellaneous loads are modeled using a simplified occupancy-based approximation. The heating, ventilation, and air-conditioning (HVAC) systems are modeled using a set of equations that approximates the total mass flow rate required to meet the sensible and latent loads of each building as a whole. Each of these simplifying approximations empowers the urban-scale simulation to have reasonable execution times on the number of buildings being simulated.

Building performance simulation is a mature domain of research relative to urban scale efforts.

The use of whole building simulation engines originated in the 1960's with the US government's development of the BLAST and DOE-2 hourly energy simulation programs (Lawrie et al. 2001). In 1996, development on a new simulation engine, EnergyPlus, began in order to combine the advantages of previous efforts in a single, modular program. EnergyPlus, as a result, has become a popular choice in detailed whole-building performance simulation due to the breadth of mechanical, renewable, and electrical systems that can be modeled. EnergyPlus specifically excels in its ability to model unique mechanical system types such as decoupled centralized cooling (Miller and Sekhar 2010). Additionally, EnergyPlus is designed to provide a high resolution in which internal loads and natural ventilation technologies can be modeled in detail at the building level. EnergyPlus is also extensively used within the research community and has new features that enable it to couple with other simulation programs.

Both building and urban-scale simulation domains have rightfully chosen boundary conditions that reflect their key goals while seeking to minimize the input parameters necessary and run-times of the engines themselves. This focus results in certain deficiencies concerning modeling various phenomena. For example, urban scale simulation highly simplifies the building systems and internal load models, thus making a retrofit analysis at the systems level difficult. And whole building simulation in EnergyPlus neglects many of the various contextual consideration of the urban environment such as long-wave radiation exchange with adjacent surfaces and localized urban weather effects (Lawrie et al. 2001).

The current effort seeks to couple building and urban scale simulation to address the deficiencies of the individual engines. The research in this paper is part of a larger coupling effort in which various engines are connected and co-simulated to create a more comprehensive analysis of the urban scale (Dorer et al. 2013; Allegrini, Dorer, and Carmeliet 2012). The target is the computational interface between the building energy model, using EnergyPlus, and the urban energy model using CitySim. An overview of the larger scope is shown in Figure 1 and the context of the coupling task appears as the interface between the City Energy Simulation (CES) model and the Building Energy Simulation (BES) model. The scales and models contained in the urban environment context include the Urban-Scale Model (UC Model), the Urban Microclimate (UMC) model using OpenFoam, and the Meteorological Meso-scale (MM model) using Climate Limited-Area Modeling (COSMO-CLM). On the database side, Revit, Global Information Systems (GIS), and building information systems (BIS) are utilized.

The coupling and co-simulation process is implemented on two case studies in Switzerland. The first case study is the ETH Zürich Hoenggerberg campus in Zürich, Switzerland. It was modeled in the CitySim simulation engine and co-simulated using work-flow automation. The target of this case study is to evaluate the differences between the coupled and solo EnergyPlus simulations based on the variables exchanged. This scenario includes the use of measured data for heating and cooling within their respective seasons to compare to the simulation results. The second case study is the EPFL campus in Lausanne, Switzerland. The objective of this scenario is to evaluate the differences between coupled and uncoupled versions of the CitySim simulation engine.

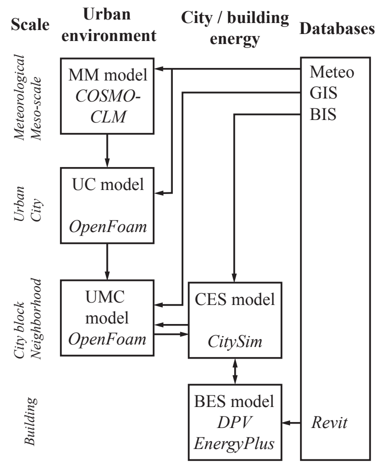

Figure 1. EnergyPlus and CitySim coupling are part of the wider context. Each block in the diagram represents an environment, with the tool/engine name in italics ((Thomas et al. 2014), adapted from (Dorer et al. 2013))

This paper describes the achievement of several objectives. The first is to automate the process of simultaneous meta-data extraction from a Building Information Model (BIM) for the creation of both building and urban-scale performance models for a real-world campus of buildings. Next, we week to co-simulate the urban and building scale models through concurrent information exchange. Finally, we implement a simplified calibration procedure for the first scenario by reconciling the co-simulation output results for a target building using measured energy performance data from the campus energy information system (EIS)

The first two objectives have been demonstrated in a simplified context in previous literature (Thomas and Schlueter 2012; Miller et al. 2015). The innovation in the current publication is an extension of this research through the modeling and co-simulation of real-world case studies. With respect to the third contribution, to the best of the authors' knowledge, no previous study has compared the results of a building and urban-scale co-simulation procedure to measured data from a real-world campus.

1.1. *Previous multi-scale coupling studies*

Previous attempts of information exchange have been implemented between simulation engines at various scales. Much of the initial co-simulation work in the literature is done at the subsystem and building-scale. Previous studies have analyzed strong and loose coupling of engines at this scale (Wetter 2011; Trčka, Hensen, and Wetter 2010). Coupling of building-scale simulation with urban-scale computational fluid dynamics (CFD) is attempted for modeling natural ventilation (Zhang et al. 2013) and to improve energy prediction (Bouyer, Inard, and Musy 2011). A comprehensive review of energy and airflow modeling of neighborhoods and university campuses was published that includes strategic aspects of coupling different types of models (Srebric, Heidarinejad, and Liu 2015). EnergyPlus has been coupled with ENVI- met, a micro-climate computational fluid dynamics (CFD) program (Yang et al. 2012). It was also coupled with simplified lumped parameter models to facilitate comparison with measured sensor data (Martin et al. 2015). While not directly coupled, EnergyPlus and the TEP Urban Canopy Model program were connected through a modified weather file to quantify the influences of urban localized weather effects on whole building simulation (Bueno et al. 2011) and urban weather generation (Bueno et al. 2013).

2. Methodology

2.1. *Coupling process*

The coupling process of a simplified single zone model and contextual surrounding buildings is described in previous studies (Thomas et al. 2014), which forms the basis for the methodology in the current effort. This process utilizes the Design Performance Viewer (DPV) and associated workflow. The DPV is a tool written to extract and simulate an EnergyPlus input data file (IDF) from an Autodesk^{TM} Revit^{TM} BIM (Schlueter and Thesseling 2009). The central philosophy behind the tool is the rapid simulation of the building information model from the earliest design possible that can be used throughout the life-cycle of the building including retrofit analysis (Miller et al. 2014). This process is achieved by augmenting the information in the BIM with default values and abstracting information not relevant for energy simulation. The tool already has a simplified notion of surrounding buildings, which are modeled in the BIM as simple mass objects without further information and are exported as shading surfaces to EnergyPlus. This functionality is used for creating the CitySim mass scene and leads to a crude model of the urban context of the building. The current DPV philosophy of allowing the designer to iterate rapidly on early design decisions based on feedback about the performance of the design remains. This approach includes streamlining the process where running a simulation requires no effort from the designer due to automatic creation of input files, execution, and analysis of the results.

The coupling process of EnergyPlus and CitySim is shown in Figure 2. The solid lines depict the co-simulation of EnergyPlus and CitySim, and the dotted lines illustrate solo simulations of either EnergyPlus or CitySim. First, the DPV is used to extract an EnergyPlus simulation model from the BIM. The DPV utilizes the Revit API to extract geometrical information about the building and the physical properties of walls, windows, doors, roofs, and floors. This information is encoded in the BIM model as wall types, roof types, floor types as well as window and door families. Wherever possible, the tool uses the layering and materials of the construction types, enhancing them with physical attributes relevant to EnergyPlus. Where not defined, it assumes default values.

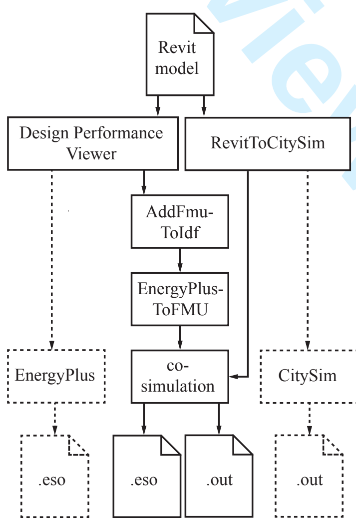

Figure 2. Overview diagram of the coupling process including tools and outputs (Thomas et al. 2014)

Next, geometry is created to be used in both the CitySim and EnergyPlus models as buildings and surfaces surrounding the building targeted in the IDF. This feature of the DPV is used for including shading surfaces in the EnergyPlus simulation model: it uses so-called *mass objects* in the BIM model as surrounding buildings. The DPV model views these buildings as a series of shading surfaces. A transformation is added to the DPV model that produces an input file for the CitySim

solver. This file uses an XML format describing the buildings in a scene for simulation, including their construction types, geometry, and systems for heating and cooling. The main BIM is extracted to the CitySim scene as one of the buildings to be simulated, with the properties of the construction types matching those in the DPV model. The glazing ratio is calculated based on the window and wall areas of the DPV model. Shading surfaces are grouped into buildings based on the mass object from which they were extracted. These adjacent buildings use default construction properties for walls and roofs, and we assign them a default glazing ratio. These defaults can be overridden by custom properties applied to the mass objects in the BIM much in the same way as the model elements of the main building are enriched with DPV information.

As of version 8.1.0, EnergyPlus supports exporting a simulation model as a Functional Mock-up Unit (FMU) (Nouidui, Wetter, and Zuo 2014). This feature introduces new IDF objects to specify the interface such an FMU exposes. These objects define which output variables are exported by the FMU and which variables are imported. The FMU export functionality is closely linked to the Energy Management System (EMS) of EnergyPlus. Co-simulation exchange variables either mimic an EnergyPlus schedule, an EMS variable or drive an EMS actuator. Since the model used by CitySim to simulate a building is more abstract than the model used by EnergyPlus, the EMS is used to aggregate certain values. CitySim does not model windows separately. Therefore, a weighted average of window and wall surface temperatures is calculated with EMS subroutines.

The FMU creation process is the basis for coupling the two models at each timestep in the simulation. Figure 3 illustrates this process from both the EnergyPlus and CitySim perspective. The augmented IDF file is fed to the *EnergyPlusToFMI* script (Nouidui and Wetter 2014). Once configured, this script produces an FMU file based on the augmented IDF file and the weather file to be used as well as a DLL file implementing the Functional Mock-up Interface that can load the IDF file, locate EnergyPlus and run the simulation.

The number of timesteps per hour for both CitySim and EnergyPlus is set to one per hour. The frequency of data exchanges is set to once per timestep. No data averaging over time is performed. Data exported from one simulation engine overwrites the corresponding data in the other simulation engine at each timestep. Each simulation is performed for a whole year.

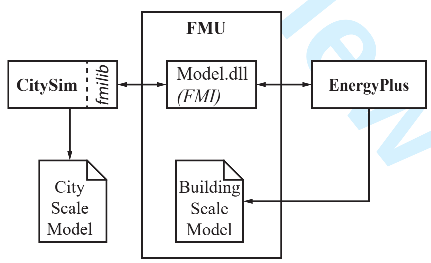

Figure 3. Simulation information exchange between CitySim and EnergyPlus using FMI (Thomas et al. 2014)

2.2. *Coupled variables*

Several key urban-scale weather variables are sent to EnergyPlus from CitySim to account better for the localized effects of surrounding buildings, geography and climate conditions. These variables are outlined in Table 1. They include various outdoor air conditions such as dry bulb and wet bulb temperatures, dew-point, humidity, wind speed and direction, and direct and diffuse solar radiation. These variables overwrite the input weather variables that EnergyPlus obtains from its weather file input. CitySim is designed to account for physical phenomenon inherent to urban environments, which are often neglected in building-scale simulation environments (Robinson and Stone 2004; Robinson et al. 2009). CitySim can be connected to a simplified micro-climate airflow model that can predict local climatic conditions around each building. Long-wave radiation exchange between the simulated building and its surroundings is sent to EnergyPlus; this process is described in detail in Section 2.3. Finally, CitySim shares its calculated occupancy schedules as it can use a deterministic or stochastic occupant behavior model, whereas EnergyPlus models are solely a deterministic models (Haldi and Robinson 2011).

Table 1. Values sent to EnergyPlus from CitySim by the FMU

Object	Variable Name	Description
Outdoor	Outdoor Drybulb	The outdoor dry-bulb temperature in °C
	Outdoor Dewpoint	The outdoor dewpoint temperature in °C
	Outdoor Relative Humidity	The outdoor relative humidity expressed in percent.
	Diffuse Solar	Diffuse horizontal irradiance in W/m^2
	Direct Solar	Beam normal irradiance in W/m^2
	Wind Speed	The outdoor wind speed in m/s
	Wind Direction	The wind direction in degrees (N=0, E=90, S=180, W=270)
Long-Wave Radiation	Environmental Radiant Temp.	Calculated T_{env} from the sky, ground, and surrounding surfaces
	Environmental Radiant Heat Gain Coefficient	Calculated h_{env} from the sky, ground, and surrounding surfaces
Zone	Occupation	Fraction of the maximum occupation (0.0-1.0) overrides the EnergyPlus occupation schedule with the CitySim stochastic schedule.

Variables sent to CitySim by EnergyPlus at each time step include several variables related to the calculation of heating and cooling loads of a targeted building. Table 2 outlines this list of exchanged variables. These variables are transferred due to the ability of EnergyPlus to model more detailed building systems, schedules, ventilation and internal load types than CitySim. For example, EnergyPlus is flexible enough to model a detailed radiant heating and cooling system that would be impossible in CiytSim. EnergyPlus is an engine optimized to accurately model building-scale systems. Thus, CitySim can take advantage of these models through coupling and co-simulation. EnergyPlus sends the heating and cooling loads, the surface temperatures of the exterior surfaces and the ventilation flow rates to CitySim.

Table 2. Values sent to CitySim from EnergyPlus by the FMU

Object	Variable Name	Description
Wall, Roof	Outside Surface Temperature	The temperature on the outside of the surface in °C
Wall	Average Outside Surface Temperature	The (weighted) average temperature of the surface on the outside in °C.
Zone	Total Heating Energy	The heating energy in Joules used in this timestep.
	Total Cooling Energy	The cooling energy in Joules used in this timestep.
	Zone Mean Air Temperature	The mean air temperature in the zone in °C
	Ventilation Volume Flow Rate	The flow rate in m^3/s (standard density)

2.3. *long-wave radiation exchange*

long-wave radiation exchange in the urban scale environment is coupled in the co-simulation process. It requires the development of a set of approximations to reduce the number of coupled variables between the engines and to account for differences in the methods by which each engine calculates this value. A detailed description of long-wave Radiation (LWR) variable exchange and approximation is found in a previously published study (Miller et al. 2015) on a simplified theoretical case.

In EnergyPlus, LWR exchange for a surface is calculated through the summation of radiation gain from the ground, sky, and air as seen in Equation 1 and Figure 4a (United States Department of Energy (DOE) 2015). The radiant heat transfer coefficient for each of these environmental variables is calculated according to Equation 2 with σ as the Stefan-Boltzmann constant, ϵ as the emissivity and $F_{variable}$ being the view factor to the variable that can be sky, grd (ground) or air. A major assumption of this approach is that the modeled building's surfaces and those of adjacent buildings are at a uniform temperature and the LWR radiation exchange is negligible; a situation that is an

oversimplification in an urban scale domain (Evins, Dorer, and Carmeliet 2014).

$$Q_{LWR,EnergyPlus} = h_{r,grd}(T_{surf} - T_{grd}) + h_{r,sky}(T_{surf} - T_{sky}) + h_{r,air}(T_{surf} - T_{air}) \quad (1)$$

$$h_{r,variable} = \frac{\epsilon\sigma F_{variable}(T_{surf}^4 - T_{variable}^4)}{T_{surf} - T_{variable}} \quad (2)$$

In comparison, CitySim calculates LWR exchange by calculating an aggregated equivalent temperature, T_{env}, and radiative heat transfer coefficient, $h_{r,env}$, from surrounding urban surfaces in addition to ground, sky, and air (Robinson et al. 2009). The calculation for T_{env} is expressed in Equation 3 with the F values being view factors of the surrounding environment including adjacent surfaces $i = 1..n$. $h_{r,env}$ is based on a first order Talyor development of the numerator of Equation 2 around $(T_{surf} + T_{variable})/2$ and therefore $Q_{LWR,CitySim}$ is calculated using Equation 4.

$$\sigma T_{env}^4 = \sigma F_{sky} T_{sky}^4 + \sigma F_{grd} T_{grd}^4 + \sum_{i=1}^{n} \epsilon_i \sigma F_i T_i^4 \quad (3)$$

$$Q_{LWR,CitySim} = h_{r,env}(T_{surf} - T_{env}) \quad (4)$$

In the coupled simulation, EnergyPlus uses the CitySim supplied equivalent $h_{r,env}$ and T_{env} to calculate weighted $h_{r,sky}$, $h_{r,grd}$, and $h_{r,air}$ values using the view factors and the sky-to-air split ratio. Figure 4 illustrates the schematic differences between the solo and coupled simulations on a theoretical example of a target building with two adjacent buildings with surfaces available for radiation exchange.

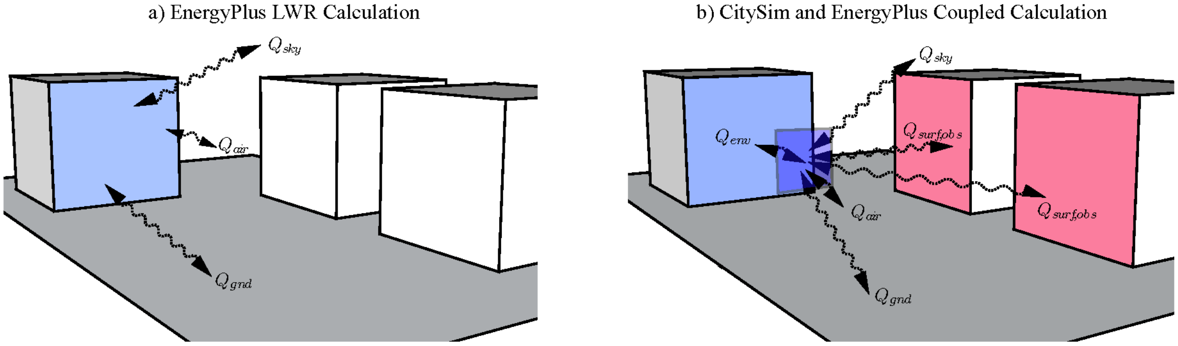

Figure 4. Comparison of the LWR components between a) Solo EnergyPlus and b) Coupled CitySim/EnergyPlus configuration (Miller et al. 2015)

2.4. *Work flow automation*

The coupling, simulation and co-simulation process is completely managed within a program called VisTrails (Freire et al. 2014). The implementation of this type of workflow is outlined in previous work focused on automating DPV using the Kepler platform (Thomas and Schlueter 2012). This process reduces the effort expended by a designer down to pressing a single button. This functionality allows an iterative design informed by readily available simulation results. An automated workflow ties the various steps together and maintains the effortless iterative design process. VisTrails enables the coupling of various workflow subprocesses script initializations, executions of the engines, and

the compilation of the outputs. This tool empowers the coupling of multiple executable files and their connecting scripts in graphical diagrams that enhance reproducibility and process automation (Freire et al. 2014). The VisTrails workflow diagram for the first case study in this paper is seen in Figure 5.

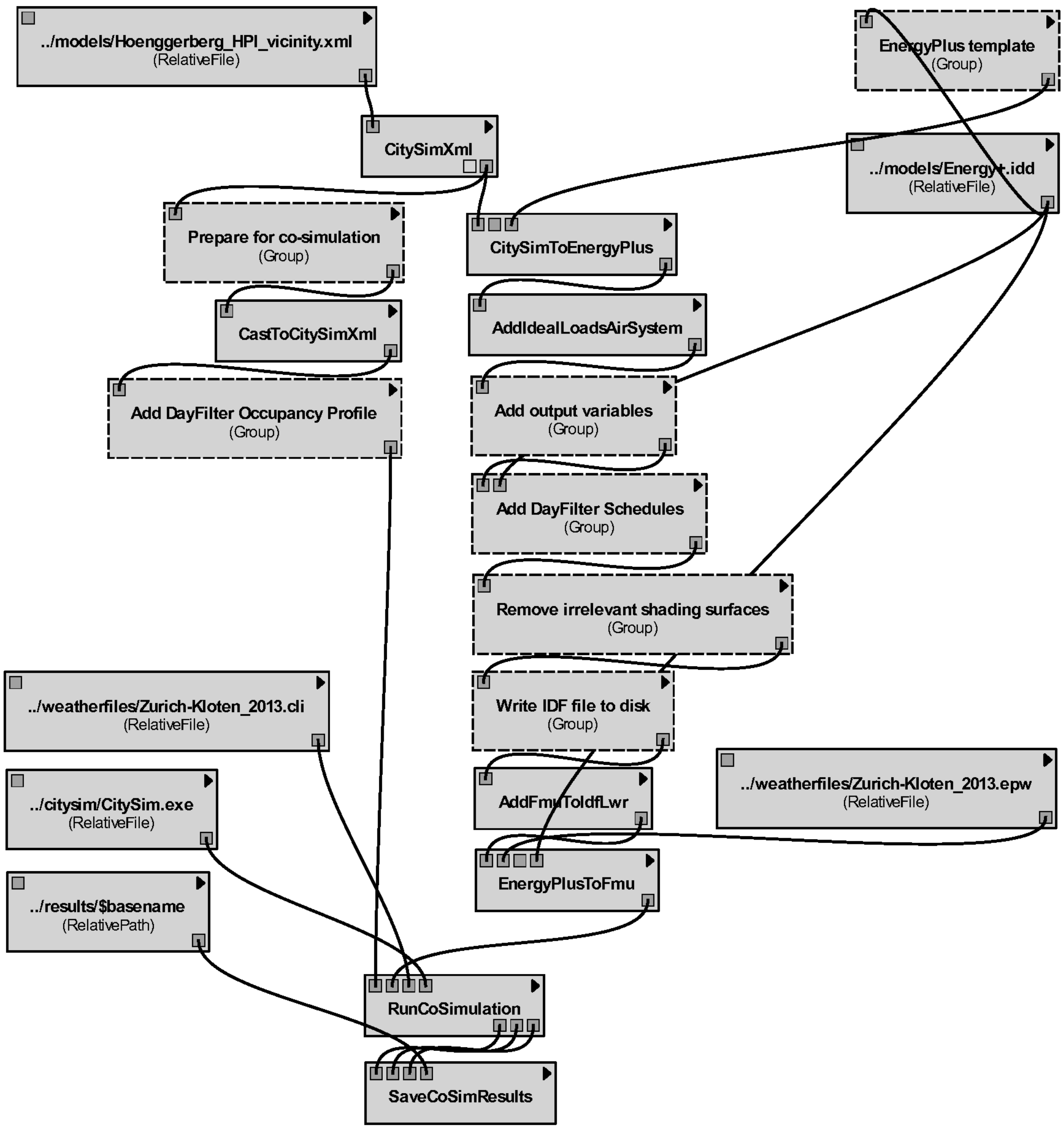

Figure 5. Workflow in VizTrails

2.5. *Simplified calibration*

In the first case study, one aspect of this analysis is the comparison of the actual measured performance of the target building on campus with the simulation results of the co-simulation. A simplified calibration procedure is adapted from previous research to compare the measured heating and cooling data available on campus with various simulation scenarios (Samuelson, Ghorayshi, and Reinhart 2015). This calibration procedure was utilized in the performance reconciliation of 18 buildings that were built according to the LEED Canada protocol and were under review of actualized performance. This protocol is unique in its analysis process to uncover design model deficiencies in a step-wise manner, utilizing the most readily available knowledge first and working towards equilibrium between measured and simulated. There is an appropriate balance between the effort of implementation and value generated through the calibration process.

3. Implementation

The co-simulation process is implemented on two case studies in Switzerland. The first is the ETH Zürich Hoenggerberg campus in Zürich, Switzerland. The focus of this case study is to quantify the impact of the information exchange through co-simulation within the EnergyPlus engine. The intent on this campus was to develop techniques for retrofit analysis using EnergyPlus. The targeted building on this campus is the HPI Building. Raw measured data is available for many of the buildings on campus, thus a simplified calibration procedure is used to reconcile the simulation results.

The second case study is the EPFL campus in Lausanne, Switzerland. The targeted building, in this instance, was the Quartier Nord complex. The focus of this study was to compare the solo and co-simulation output results of CitySim. Reliable measured data for calibration is not currently available for this building.

3.1. *Campus case study 1: ETHZ Hoenggerberg Campus*

The ETH Zürich Hoenggerberg campus includes 32 higher education facilities with spaces allocated to laboratories, office space, lecture halls, cafeterias, data centers and other types of similar areas. The campus has a centralized energy management system (EMS) that contains 807 energy and water measurement points from heating, cooling, electricity, city gas, domestic hot water, gray water, and general water consumption.

The focus of the co-simulation process is that the performance of a targeted building is evaluated through solo and coupled methods. The HPI building on campus was chosen in this case study due to the amount and quality of measured data available from the EMS for this building. HPI is a 2,610 square meter building that is made up mostly of office space and classrooms. It also includes 400 m^2 convenience store and coffee shop. The building is indicated on a campus map shown in Figure 6 and is shaded red.

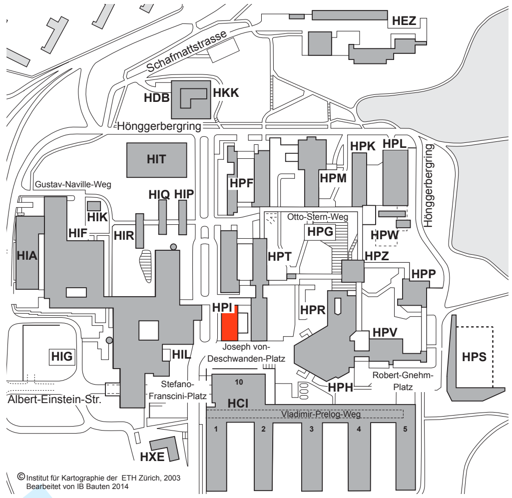

Figure 6. ETH Hoenggerberg campus map with the HPI building shaded red

3.2. *Model development*

In order to perform a co-simulation of the targeted buildings, initially a CitySim model of the campus was developed. Through the workflow automation process, this geometry was converted into an EnergyPlus input file as seen in Figure 7. The EnergyPlus input file was then used as an input to execute EnergyPlus solo and co-simulation processes for the purpose of simplified calibration, and then to understand the magnitude of the difference between these simulation scenarios.

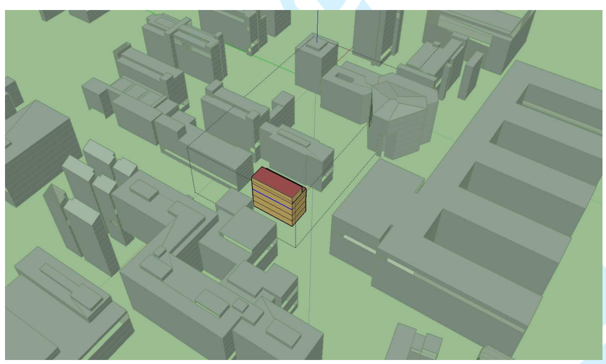

Figure 7. The HPI building EnergyPlus model extracted from the CitySim model. The HPI building is seen as the light and dark brown building in the center surrounded by gray masses that represent other buildings on campus. The graphic is illustrated with OpenStudio for Sketch-up.

3.3. *Measured data collection and calibration*

Energy data from the HPI building was collected and analyzed in the context of the simplified calibration procedures. The measured datasets were screened and aggregated into typical usage profiles to be used for the lighting, plug- loads, and HVAC equipment availability schedules and power densities. Figure 8 illustrates the aggregation examples of electrical energy for the HPI building. This profile was created through a filtering and clustering process known as *DayFilter* (Miller, Nagy, and Schlueter 2015). Cluster 0 represents the typical energy profile for Sunday, while Cluster 1 dominates the Saturdays of the data set. Clusters 2 and 3 make up most of the weekdays of the data set with Cluster 3 being more common in non-summer months. These profiles are used to set the availability schedules as inputs into the EnergyPlus simulation to emulate the way occupants inhabit the building and how the building management system (BMS) controls the lighting and HVAC systems.

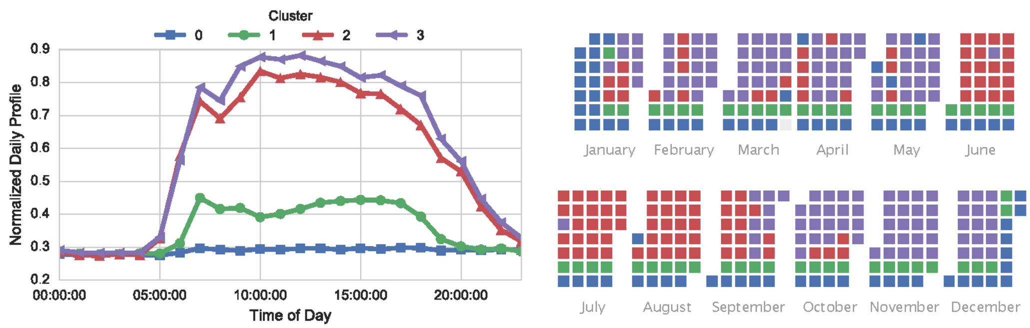

Figure 8. Typical measured data electricity profiles of (left) average daily electrical consumption for each cluster and (right) color-coded calendar of which days fall within each cluster. The diagram on the right is each month of the year with each row corresponding with a day of the week (starting with Monday) and each column corresponding to a week of the month.

The measured and simulated data from both the co-simulation and EnergyPlus solo simulation were analyzed in order to understand how both the solo and co-simulations compare to real, measured data. The calibration process was undertaken through a series of steps such as including local weather conditions for the simulation period and adding custom lighting schedules and power densities extracted from the measured data. The models were calibrated to the summer season (May-September) for cooling and the winter season (Jan-April and October to December) for heating. Figure 9 illustrates a comparison of the measured data with the simulations after the tuning process. The final calibrated EnergyPlus solo model had a normalized mean bias error (NMBE) of -9.36% and a coefficient of variation of root mean square error (CVRMSE) of 21.7% for cooling and 5.02% and 29.4% for heating. These metrics fall within the +/-10% NMBE and +/-30% CVRSME used in this case study for calibration. A total of 37 calibration iterations were undertaken to modulate the simulation results to within these criteria. The goal of calibration, in this case, is to just bring the models to within a reasonable range of reality in order to bring more confidence to analysis of the discrepancies between the solo and co-simulation scenarios.

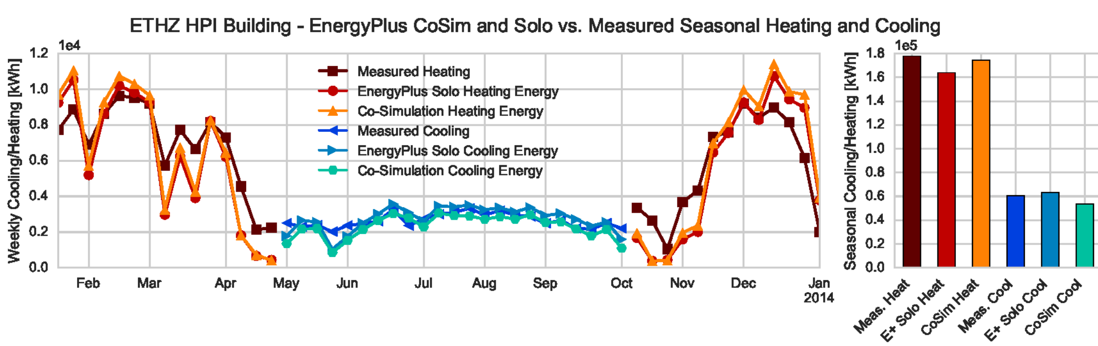

Figure 9. HPI Measured vs. Co-Simulation and EnergyPlus Solo for Heating and Cooling Seasons

3.4. *EnergyPlus co-simulation results*

For cooling, a discrepancy can be seen between co- simulation and solo EnergyPlus. Co-simulation decreases the predicted cooling energy by 15.5%, as seen in Figure 10. Figure 11 illustrates the difference in predicted heating energy consumption across the test year. A consistent offset exists across the time frame of days in January, the peak of the heating season. A more varied discrepancy across the heating months is noticed resulting an overall increase of heating prediction of 6.5% due to co-simulation. The exchange of long-wave radiation for this particular site is substantial due to the proximity of surrounding buildings.

When comparing the solo and co-simulated models to the measured data, it is noticed that cooling energy is over-predicted by the solo simulation by 4%, while co-simulation under-predicted by 11.1%. This discrepancy is likely due to a loss in long-wave radiation in the co-simulation to the surrounding buildings, thus reducing the overall cooling load.

For heating energy, co-simulation was able to bring the predicted value to within 2% of the measured value for the year, an improvement as compared to the solo simulation, which was 8.5% less than the measured value. This situation is also likely due to the long-wave radiation loss to surrounding buildings, thus increasing the overall heating load.

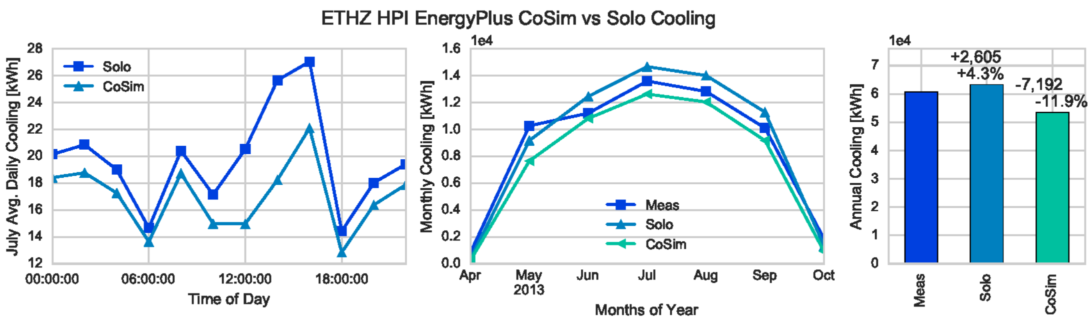

Figure 10. HPI Co-Simulation vs. EnergyPlus Solo for Cooling

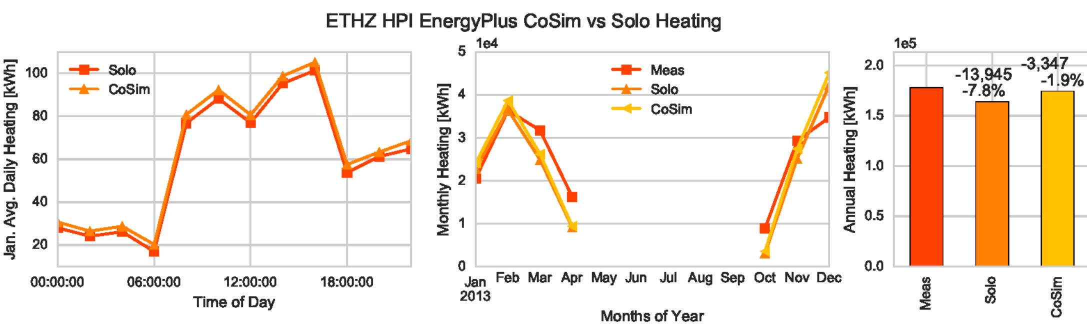

Figure 11. HPI Co-Simulation vs. EnergyPlus Solo for Heating

3.5. *Campus case study 2: EPFL Quartier Nord*

Quartier Nord is a whole new quarter of the École Polytechnique Fédérale de Lausanne (EPFL) campus located at its northwest corner. This complex includes a Convention Centre with an auditorium with a maximum capacity of 3000 (seated) people, housing for 516 students, retail and service areas and a hotel. As a public space, this ensemble is organized around the central plaza as seen in Figure 12). With a particularly strong visual and formal identity, the SwissTech Convention Centre (STCC) is clearly the key protagonist. Designed as a Minergie building, it includes modern energy conversion technologies to reduce its energy consumption. The focus of the co-simulation is realized on the STCC, simulated with the nearby buildings for housing, retail and service areas (Beyeler, Beglinger, and Roder 2009).

Figure 12. The Quartier Nord at EPFL in Lausanne

3.6. *Model development*

The information required in the simulation mainly comprises three parts: physical, geometrical and operational data. The geometry information including the shape, dimension, structure and materials was obtained from the Real Estate and Infrastructure Department of École Polytechnique Fédérale de Lausanne (EPFL), which was responsible for carrying out the project from call to tender to construction. However, since the documents provided were conflicting with what has been installed, the task to realize a precise model of the buildings itself is rather tedious. Besides, it is even more challenging to get the operational data (daily occupancy, lighting, and electrical equipment usage level and ventilation rate) as the building has only recently been set in operation mode and as engineers and technicians have been working on improving the controls. Therefore, due to unreliable monitoring data, the calibration step of the model was not undertaken.

Considering the lack of detailed information about the building, a so-called detailed reference case was modeled with EnergyPlus (Mauree et al. 2015) in which regulation standards applied in the design phase from the local building code norms were used to complete the missing information. A rendering of this model is seen in Figure 13.

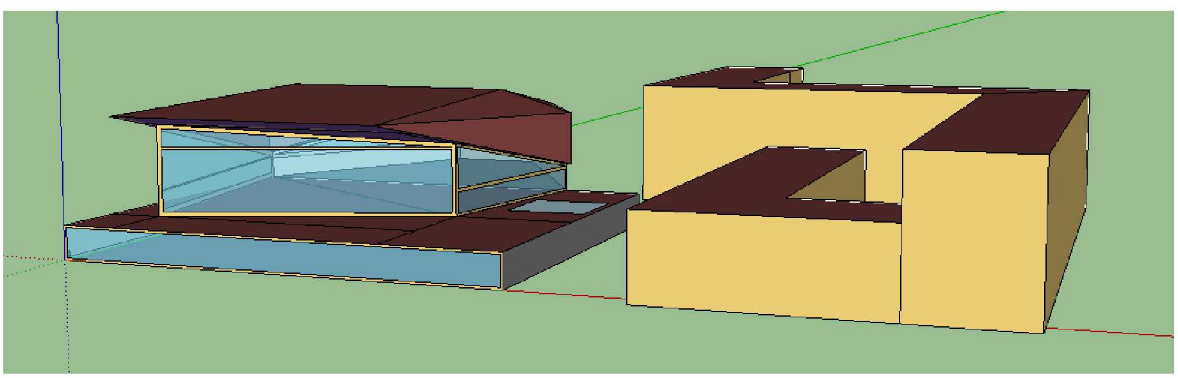

Figure 13. The Quartier Nord modeled with OpenStudio for Sketchup[2]. The STCC on the left is the main focus of the study and is represented by two thermal zones.

The corresponding CitySim model was created by exporting a DXF file from EnergyPlus for the whole of Quartier Nord, and importing it into the Graphical User Interface of CitySim. Physical characteristics of the building were added to complete the CitySim model. Finally, the same script as described in Section 2 was used to export the model from CitySim to EnergyPlus, giving a simplified EnergyPlus model.

3.7. *Comparison of EnergyPlus and CitySim*

Both the CitySim and EnergyPlus engines are utilized in this case study. The first comparison to observe is the differences between the two engines when focused on the STCC building. When simulated in isolation, the CitySim engine predicts a 28.6% increase in heating load and a 44.4% increase in cooling load as compared to EnergyPlus. This phenomenon is due to the differences in the way each of these engines calculates heating and cooling loads. CitySim has a much more simplified model of building occupants, lighting, and plug loads. CitySim also includes long-wave radiation exchange calculations that can greatly influence the heating and cooling load calculations as well. Use of the co-simulation process brings the engines to within 5.4%. Figure 14 illustrates these differences for cooling and Figure 15 for heating.

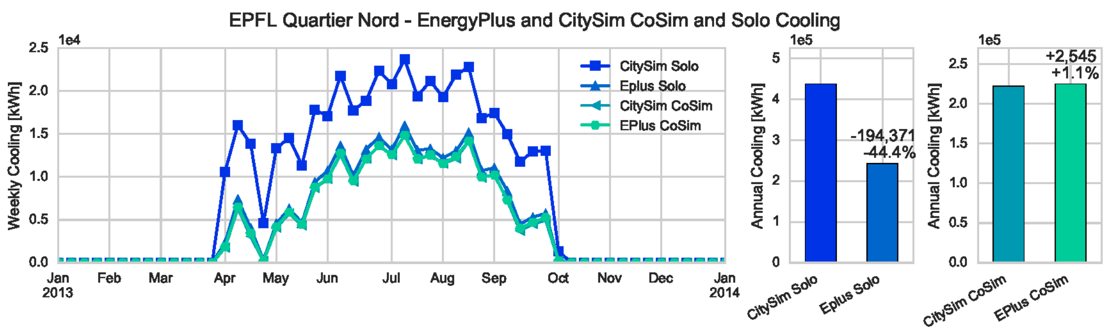

Figure 14. STCC CitySim vs. EnergyPlus Solo for Cooling

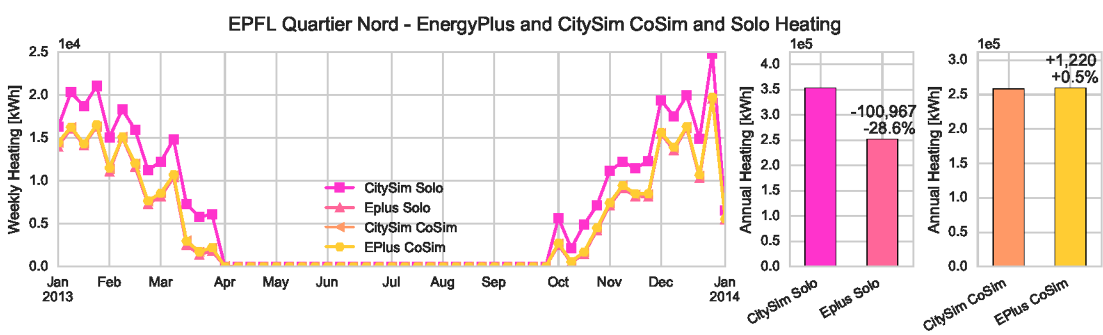

Figure 15. STCC CitySim vs. EnergyPlus Solo for Heating

3.8. *EnergyPlus co-simulation results*

The STCC building is also simulated within the solo and co-simulation environments. When focusing on the EnergyPlus results, a 7.5% decrease in cooling energy is observed, as seen in Figure 16. A 2.8% increase in heating energy is observed, as seen in Figure 17. These differences are less pronounced than the HPI and theoretical case studies due to the number and proximity of surrounding buildings is not as large. long-wave radiation exchange in this situation doesn't have as large of an impact on the heating and cooling calculations.

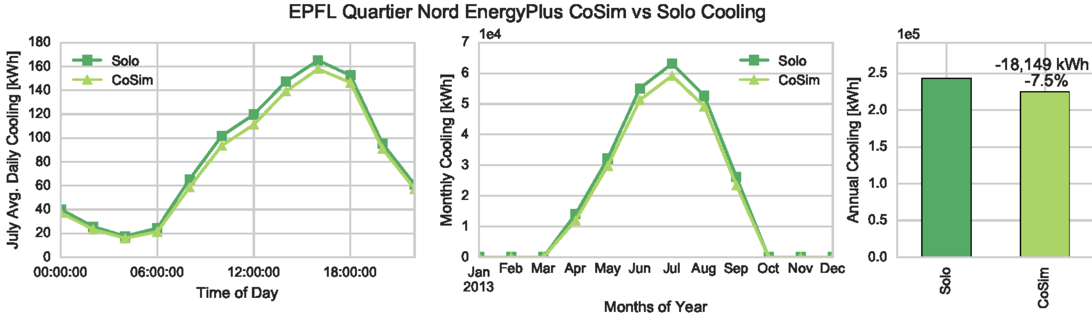

Figure 16. Quartier Nord EnergyPlus Co-Simulation vs. Solo for Cooling

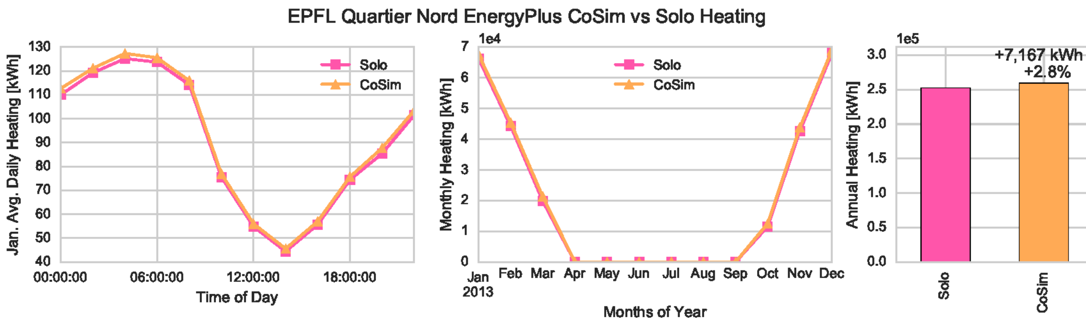

Figure 17. Quartier Nord EnergyPlus Co-Simulation vs. Solo for Heating

4. Discussion

Two campus case studies were presented in this paper to showcase a unique process of extracting model meta-data, conversion of those data into input files for two separate simulation engines, and the solo and co-simulation process of those engines on two real-world case studies. The analysis of the results shows that for the first case study, co-simulation can achieve values closer to measured reality for heating, but not cooling. These results are unique to this case study and simply show that the co-simulation process may be helpful for heating only in this particular instance. A limitation of this study is that we only analyze a single building against measured data in this context. In the second case study, significant discrepancies are found between the CitySim and EnergyPlus engines which were corrected using the co-simulation process.

One of the key insights in this work is that each of the engines is enabled to account for the various physical phenomenon in their simulation process that were previously impossible. For example, through co-simulation, EnergyPlus was able to utilize the long-wave radiation exchange capabilities of CitySim. The ability to couple and leverage the best aspects of multiple simulation engines can enhance the modeling of large-scale urban agglomerations.

Disadvantages of the co-simulation process are mainly centered upon the increase in computing time and power needed for the FMI to coordinate data exchange between the two simulation engines. After calibration, a comparison of the run-times of the co-simulation and solo EnergyPlus simulations show that the execution time for the solo EnergyPlus simulation was 1 minute and 49 seconds compared to 28 minutes and 10 seconds for the co-simulation.

5. Conclusion

This paper outlines the implementation of a fully automated workflow process that extracts geometry information at the urban-scale, creates the necessary input information, executes each engine with information exchange at each time step of targeted variables, and accumulates the results of the analysis. The process has been implemented on simplified theoretical scenarios in the past, and the key innovation with this work is in implementation on actual case study campuses and targeted buildings. The results illustrate that the differences between the co- simulation and solo environments are within range of previous theoretical models. More reliable results of the magnitude of differences between the simulation techniques can be extracted from these real-world scenarios.

Future work in using co-simulation models for buildings and campuses would more intensively utilize the model results in a practical implementation of retrofit scenarios or urban-scale energy systems research. More implementations would also test the feasibility of using co-simulation for retrofit analysis, urban planning studies, and cooling and heating system optimization.

5.1. *Acknowledgments*

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Research Article

Urban and building multiscale co-simulation: case study implementations on two university campuses

(*Submission for review on April 30, 2016*)

~~The co-simulation of both urban and building-level models leverages the advantages of both platforms. It better accounts for the localized effects of surrounding buildings, geography and climate conditions while maintaining high-fidelity building systems representation.~~ This paper describes the co-simulation process of the building and urban scale models of two ~~university campuses in Switzerland using EnergyPlus and CitySim.~~ campuses of higher education buildings in Switzerland. The campuses are modeled at both the building level, using the EnergyPlus simulation engine, and at the urban scale using the CitySim engine. A co- simulation framework is used to execute simulations from both engines concurrently with an exchange of information to leverage the various strengths of each. In the first case study, on-site weather and measured performance data ~~is~~ are then compared to the output from two modeling scenarios: building-scale simulation using EnergyPlus and co-simulation ~~results. The~~ of the engines. A partial calibration process is implemented to reconcile the simulations with the measured data of a targeted office building on campus. In the second case study~~examines the results of the two~~ , the co-simulation results are compared to the both the CitySim simulation and EnergyPlus engines. The results show that coupling of EnergyPlus with CitySim resulted in a -15.5% and -7.5% impact on cooling consumption and a +6.5% and +4.8% impact on heating ~~use as compared to solo simulations. The co-simulation process was able to better model realistic conditions for heating, but not cooling in one case study. It was able to substantially reduce the discrepancies in prediction between the engines in the other study.~~

consumption. Challenges encountered with the urban scale calibration and the strengths and weaknesses of the developed process are discussed.

Keywords: Building-scale simulation, Calibrated energy models, CitySim, Co-simulation, EnergyPlus, Urban-scale simulation

1. Introduction

Urban scale building performance simulation is a process that empowers the analysis and optimization of cities. Urban populations are growing around the world at an unprecedented rate. A transition from urban to rural is underway and 2.5 billion people are expected to join cities throughout the world ~~by the year 2050 (?)~~(United Nations 2014). Expansions of entire districts and even cities is not an uncommon phenomenon, especially in East Asia and Africa. Urban scale modeling is in the midst of an intense focus on the research community with six key areas of practice: technology design, building design, urban climate, systems design, policy assessment, and land use and transportation ~~(?)~~(Keirstead, Jennings, and Sivakumar 2012). The ability to simulate the interaction between large collections of buildings enables the development and testing of optimization and planning scenarios for this new development ~~(?)~~(Dorer et al. 2013).

The CitySim simulation engine is an example of such a program designed and optimized for urban-scale simulation. CitySim is an urban performance simulation engine that comprises a ~~solver~~ Solver module as well as a graphical user interface. It focuses on the energy flows of multiple simplified building models and their interdependent relationship with their urban climate ~~(?)~~(Robinson et al. 2009). CitySim includes building thermal, urban radiation, occupant behavior, and plant/equipment models integrated as a single simulation engine. CitySim simulates multiple buildings up to city scale using simplified models to achieve a good compromise between modeling accuracy, computational overheads, and data availability. Each building's thermal behavior is based on an electrical analogy using a two node resistor- capacitor network. The internal lighting, people, and miscellaneous loads are modeled using a simplified occupancy-based approximation. The heating, ventilation, and air-conditioning (HVAC) systems are modeled using a ~~set of equations~~ single equation that approximates the total mass flow rate required to meet the sensible and latent loads of each building as a whole. Each of these simplifying approximations empowers the urban-scale simulation to have reasonable execution times on the number of buildings being simulated.

Building performance simulation is a mature domain of research relative to urban scale efforts. The use of whole building simulation engines originated in the ~~1960's~~ 1960s with the US government's development of the BLAST and DOE-2 hourly energy simulation programs ~~(?)~~(Lawrie et al. 2001). In 1996, development on a new simulation engine, EnergyPlus, began in order to combine the advantages of previous efforts in a single, modular program. EnergyPlus, as a result, has become a popular choice in detailed whole-building performance simulation due to the breadth of mechanical, renewable, and electrical systems that can be modeled. EnergyPlus specifically excels in its ability to model unique mechanical system types such as decoupled centralized cooling ~~(?)~~(Miller and Sekhar 2010) and low exergy heating and cooling systems (Hersberger and Sagerschnig 2013). Additionally, EnergyPlus is designed to provide a high resolution in which internal loads and natural ventilation technologies can be modeled in detail at the building level.

~~EnergyPlus is also extensively used within the research community and has new features that enable it to couple with other simulation programs.~~

Both building and urban-scale simulation domains have rightfully chosen boundary conditions that reflect their key goals while seeking to minimize the input parameters necessary and run-times of the engines themselves. This focus results in certain deficiencies concerning modeling various ~~phenomena~~phenomenon. For example, urban scale simulation highly simplifies the building systems and internal load models, thus making a retrofit analysis at the systems level difficult. And whole building simulation in EnergyPlus neglects many of the various contextual consideration of the urban environment such as ~~long-wave~~ long wave radiation exchange with adjacent surfaces and localized urban weather effects ~~(?).~~

~~The~~ To address the deficiencies of the individual engines, the current effort seeks to couple building and urban scale simulation~~to address the deficiencies of the individual engines~~. The research in this paper is part of a larger coupling effort in which various engines are connected and co-simulated to create a more comprehensive analysis of the urban scale ~~(??)~~(Dorer et al. 2013; Allegrini, Dorer, and Carmeliet 2012). The target is the computational interface between the building energy model, using EnergyPlus, and the urban energy model using CitySim. An overview of the larger scope is shown in Figure 1 and the context of the coupling task appears as the interface between the City Energy Simulation (CES) model and the Building Energy Simulation (BES) model.

~~The scales and models contained in the urban environment context include the Urban-Scale Model (UC Model), the Urban Microclimate (UMC) model using OpenFoam, and the Meteorological Meso-scale (MM model) using Climate Limited-Area Modeling (COSMO-CLM). On the database side, Revit, Global Information Systems (GIS), and building information systems (BIS) are utilized.~~

The coupling and co-simulation process is implemented on two case studies in Switzerland. The first case study is the ETH Zürich Hoenggerberg campus in Zürich, Switzerland. ~~It~~ The campus was modeled in the CitySim simulation engine and co-simulated using work-flow automation. The target of this case study is to evaluate the differences between the coupled and solo EnergyPlus simulations based on the variables exchanged. This scenario includes the use of measured data for heating and cooling within their respective seasons to compare to the simulation results. The second case study is the EPFL campus in Lausanne, Switzerland. The objective of this scenario is to evaluate the differences between coupled and uncoupled versions of the CitySim simulation engine.

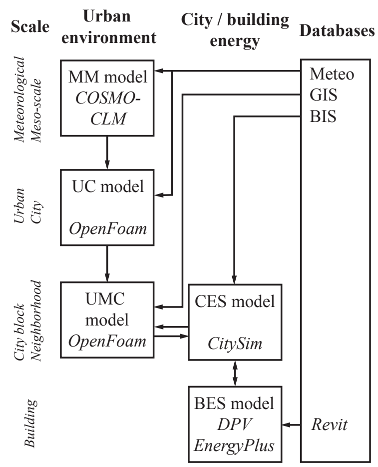

Figure 1. EnergyPlus and CitySim coupling are part of the wider context. Each block in the diagram represents an environment, with the tool/engine name in italics (~~(?)~~(Thomas et al. 2014), adapted from ~~(?)~~(Dorer et al. 2013))

This paper describes the achievement of several objectives~~. The first is to automate~~:

(1) Automation of the process of simultaneous meta-data extraction from a ~~Building Information Model~~ building information model (BIM) for the creation of both building and urban-scale performance models for a real-world campus of buildings ~~. Next, we week to co-simulate~~
(2) Co-simulate the urban and building scale models through concurrent information exchange ~~.~~ ~~Finally, we implement~~
(3) Implement a simplified calibration procedure ~~for the first scenario by~~ based on reconciling the co-simulation output results for a target building using measured energy performance data from the campus energy information system (EIS)

The first two objectives have been demonstrated in a simplified context in previous literature ~~(??)~~(Thomas et al. 2014; Miller et al. 2015). The innovation in the current publication is an extension of this research through the modeling and co-simulation of real-world case studies. With respect to the third contribution, to the best of the authors' knowledge, no previous study has compared the results of a building and urban-scale co-simulation procedure to measured data from a real-world campus.

1.1. *Previous multi-scale coupling studies*

Previous attempts of information exchange have been implemented between simulation engines at various scales. Much of the initial co-simulation work in the literature is done at the subsystem and building-scale. Previous studies have analyzed strong and loose coupling of engines at this scale ~~(??)~~(Trčka, Hensen, and Wetter 2010; Wetter 2011). Coupling of building-scale simulation with urban-scale computational fluid dynamics (CFD) is attempted for modeling natural ventilation ~~(?)~~ (Zhang et al. 2013) and to improve energy prediction ~~(?)~~(Bouyer, Inard, and Musy 2011). A comprehensive review of energy and airflow modeling of neighborhoods and university campuses was published that includes strategic aspects of coupling different types of models ~~(?)~~(Srebric, Heidarinejad, and Liu 2015). EnergyPlus has been coupled with ENVI- met, a microclimate computational fluid dynamics (CFD) program ~~(?)~~(Yang et al. 2012). It was also coupled with simplified lumped parameter models to facilitate comparison with measured sensor data ~~(?). While not directly coupled,~~ (Martin et al. 2015). EnergyPlus and the TEP Urban Canopy Model program were ~~connected through a modified weather file~~ coupled to quantify the influences of urban localized weather effects on whole building simulation ~~(?)~~ (Bueno et al. 2011) and urban weather generation ~~(?).~~ (Bueno et al. 2013).

2. Methodology

2.1. *Coupling process*

The coupling process of a simplified single zone model and contextual surrounding buildings is described in previous studies ~~(?)~~(Thomas et al. 2014), which forms the basis for the methodology in the current effort. This process utilizes the Design Performance Viewer (DPV) and associated workflow. The DPV is a tool written to extract and simulate an EnergyPlus input data file (IDF) from an Autodesk™ Revit™ BIM ~~(?)~~(Schlueter and Thesseling 2009). The central philosophy behind the tool is ~~the~~ a rapid simulation of the building information model from the earliest design possible ~~that~~ and can be used throughout the life-cycle of the building including retrofit analysis ~~(?)~~(Miller et al. 2014). This process is achieved by augmenting the information in the BIM with default values and abstracting information not relevant for energy simulation. The tool already has a simplified notion of surrounding buildings, which are modeled in the BIM as simple mass objects without further information and are exported as shading surfaces to EnergyPlus. This functionality is used for creating the CitySim mass scene and leads to a crude model of the urban context of the building. The current DPV philosophy of allowing the designer to iterate rapidly on early design decisions based on feedback about the performance of the design remains. This approach includes streamlining the process where running a simulation requires no effort from the designer due to automatic creation of input files, execution, and analysis of the results.

The coupling process of EnergyPlus and CitySim is shown in Figure 2. ~~The solid lines depict the co-simulation of EnergyPlus and CitySim, and the dotted lines illustrate solo simulations of either EnergyPlus or CitySim.~~ First, the DPV is used to extract an EnergyPlus simulation model from the BIM. The DPV utilizes the Revit API to extract geometrical information about the building and the physical properties of walls, windows, doors, roofs, and floors. This information is encoded in the BIM model as wall types, roof types, floor types as well as window and door families. Wherever possible, the tool uses the layering and materials of the construction types, enhancing them with physical attributes relevant to EnergyPlus. Where not defined, it assumes default values.

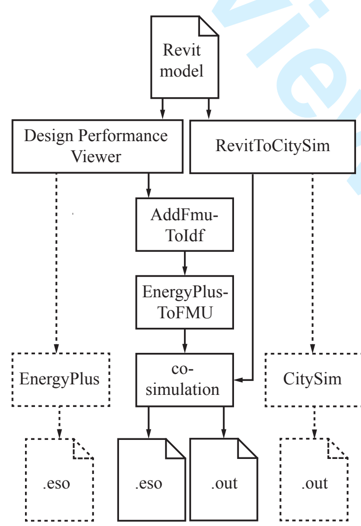

Figure 2. Overview diagram of the coupling process including tools and outputs ~~(?)~~(Thomas et al. 2014)

Next, geometry is created to be used in both the CitySim and EnergyPlus models as buildings and surfaces surrounding the building targeted in the IDF. This feature of the DPV is used for including shading surfaces in the EnergyPlus simulation model: it uses so-called *mass objects* in the BIM model as surrounding buildings. The DPV model views these buildings as a series of shading surfaces. A transformation is added to the DPV model that produces an input file for the CitySim

solver. This file uses an XML format describing the buildings in a scene for simulation, including their construction types, geometry, and systems for heating and cooling. The main BIM is extracted to the CitySim scene as one of the buildings to be simulated, with the properties of the construction types matching those in the DPV model. The glazing ratio is calculated based on the window and wall areas of the DPV model. Shading surfaces are grouped into buildings based on the mass object from which they were extracted. These ~~adjacent~~ neighboring buildings use default construction properties for walls and roofs, and we assign them a default glazing ratio. These defaults can be overridden by custom properties applied to the mass objects in the BIM much in the same way as the model elements of the main building are enriched with DPV information.

As of version 8.1.0, EnergyPlus supports exporting a simulation model as a Functional Mock-up Unit (FMU) ~~(?)~~(Nouidui, Wetter, and Zuo 2014; JModelica 2014). This feature introduces new IDF objects to specify the interface such an FMU exposes. These objects define which output variables are exported by the FMU and which variables are imported. The FMU export functionality is closely linked to the Energy Management System (EMS) of EnergyPlus. Co-simulation exchange variables either mimic an EnergyPlus schedule, an EMS variable or drive an EMS actuator. Since the model used by CitySim to simulate a building is more abstract than the model used by EnergyPlus, the EMS is used to aggregate certain values. CitySim does not model windows separately. Therefore, a weighted average of window and wall surface temperatures is calculated with EMS subroutines.

The FMU creation process is the basis for coupling the two models at each timestep in the simulation. Figure 3 illustrates this process from both the EnergyPlus and CitySim perspective. The augmented IDF file is fed to the *EnergyPlusToFMI* script ~~(?)~~(Nouidui and Wetter 2014). Once configured, this script produces an FMU file based on the augmented IDF file and the weather file to be used as well as a DLL file implementing the Functional Mock-up Interface that can load the IDF file, locate EnergyPlus and run the simulation.

~~The number of timesteps per hour for both CitySim and EnergyPlus is set to one per hour. The frequency of data exchanges is set to once per timestep. No data averaging over time is performed. Data exported from one simulation engine overwrites the corresponding data in the other simulation engine at each timestep. Each simulation is performed for a whole year.~~

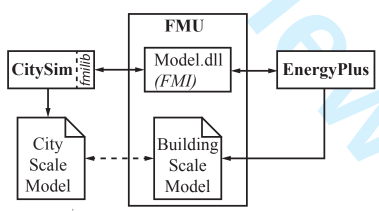

Figure 3. Simulation information exchange between CitySim and EnergyPlus using FMI ~~(?)~~(Thomas et al. 2014)

2.2. *Coupled variables*

Several key urban-scale weather variables are sent to EnergyPlus from CitySim to account better for the localized effects of surrounding buildings, geography and climate conditions. These variables ~~are outlined in Table 1. They~~ include various outdoor air conditions such as dry bulb and wet bulb temperatures, ~~dew-point~~dewpoint, humidity, wind speed and direction, and direct and diffuse solar radiation. These variables overwrite the input weather variables that EnergyPlus obtains from its weather file input. CitySim is designed to account for physical phenomenon inherent to urban environments, ~~which~~ that are often neglected in building-scale simulation environments ~~(??). CitySim can be connected to a simplified micro-climate airflow model that can predict local climatic conditions around each building. Long-wave~~ (Robinson and Stone 2004; Robinson et al. 2009). Long wave radiation exchange between the simulated building and its surroundings is sent to EnergyPlus; this process is described in detail in Section 2.3. Finally, CitySim shares its calculated occupancy schedules as it ~~can use a deterministic or stochastic occupant behavior model , whereas EnergyPlus models are solely a deterministic models (?)~~uses a more robust model of occupants behavior (Haldi and Robinson 2011).

Table 1. Values sent to EnergyPlus from CitySim by the FMU

Object	Variable Name	Description
Outdoor	Outdoor Drybulb	The outdoor dry-bulb temperature in °C
	Outdoor Dewpoint	The outdoor dewpoint temperature in °C
	Outdoor Relative Humidity	The outdoor relative humidity expressed in percent.
	Diffuse Solar	Diffuse horizontal irradiance in W/m^2
	Direct Solar	Beam normal irradiance in W/m^2
	Wind Speed	The outdoor wind speed in m/s
	Wind Direction	The wind direction in degrees (N=0, E=90, S=180, W=270)
~~Long-Wave~~ Long Wave Radiation	Environmental Radiant Temp.	Calculated T_{env} from the sky, ground, and surrounding surfaces
	Environmental Radiant Heat Gain Coefficient	Calculated h_{env} from the sky, ground, and surrounding surfaces
Zone	Occupation	Fraction of the maximum occupation (0.0-1.0) overrides the EnergyPlus occupation schedule with the CitySim stochastic schedule.

Variables sent to CitySim by EnergyPlus at each time step include several variables related to the calculation of heating and cooling loads of a targeted building. ~~Table 2 outlines this list of exchanged variables.~~ These variables are transferred due to the ability of EnergyPlus to model more detailed building systems, schedules, ventilation and internal load types than CitySim. For example, EnergyPlus is flexible enough to model a detailed radiant heating and cooling system that would be impossible in CiytSim (Hersberger and Sagerschnig 2013). EnergyPlus is an engine optimized to accurately model building-scale systems. Thus, CitySim can take advantage of these models through coupling and co-simulation. EnergyPlus sends the heating and cooling loads, the surface temperatures of the exterior surfaces and the ventilation flow rates to CitySim.

Table 2. Values sent to CitySim from EnergyPlus by the FMU

Object	Variable Name	Description
Wall, Roof	Outside Surface Temperature	The temperature on the outside of the surface in °C
Wall	Average Outside Surface Temperature	The (weighted) average temperature of the surface on the outside in °C.
Zone	Total Heating Energy	The heating energy in Joules used in this timestep.
	Total Cooling Energy	The cooling energy in Joules used in this timestep.
	Zone Mean Air Temperature	The mean air temperature in the zone in °C
	Ventilation Volume Flow Rate	The flow rate in m^3/s (standard density)

2.3. ~~long-wave~~ *Long wave radiation exchange*

~~long-wave~~ Long wave radiation exchange in the urban scale environment is coupled in the co-simulation process. It requires the development of a set of approximations to reduce the number of coupled variables between the engines and to account for differences in the methods by which each engine calculates this value. A detailed description of ~~long-wave~~ Long Wave Radiation (LWR) variable exchange and approximation is found in a previously published study ~~(?)~~ (Miller et al. 2015) on a simplified theoretical case.

In EnergyPlus, LWR exchange for a surface is calculated through the summation of radiation gain from the ground, sky, and air as seen in Equation 1 and Figure 4a ~~(?)~~(United States Department of Energy (DOE) 2015). The radiant heat transfer coefficient for each of these environmental variables is calculated according to Equation 2 with σ as the Stefan-Boltzmann constant ~~,~~ and ϵ as the emissivity~~and $F_{variable}$ being the view factor to the variable that can be sky, grd (ground) or air~~. A major assumption of this approach is that the modeled building's surfaces and those of adjacent buildings are at a uniform temperature and the LWR radiation exchange is negligible; a situation that is an oversimplification in an urban scale domain ~~(?)~~(Evins, Dorer, and Carmeliet 2014).

$$Q_{LWR,EnergyPlus} = h_{r,grd}(T_{surf} - T_{grd}) + h_{r,sky}(T_{surf} - T_{sky}) + h_{r,air}(T_{surf} - T_{air}) \quad (1)$$

$$h_{r,variable} = \frac{\epsilon\sigma F_{variable}(T^4_{surf} - T^4_{variable})}{T_{surf} - T_{variable}} \frac{\epsilon\sigma(T^4_{surf} - T^4_{variable})}{T_{surf} - T_{variable}} \quad (2)$$

In comparison, CitySim calculates LWR exchange by calculating an aggregated equivalent temperature, T_{env}, and radiative heat transfer coefficient, $h_{r,env}$, from surrounding urban surfaces in addition to ground, sky, and air ~~(?)~~(Robinson et al. 2009). The calculation for T_{env} is expressed in Equation 3 with the F values being view factors of the surrounding environment including adjacent surfaces $i = 1..n$. $h_{r,env}$ is based on a first order Talyor development of the numerator of Equation 2 around $(T_{surf} + T_{variable})/2$ and therefore $Q_{LWR,CitySim}$ is calculated using Equation 4.

$$\sigma T^4_{env} = \sigma F_{sky} T^4_{sky} + \sigma F_{grd} T^4_{grd} + \sum_{i=1}^{n} \epsilon_i \sigma F_i T^4_i \quad (3)$$

$$Q_{LWR,CitySim} = h_{r,env}(T_{surf} - T_{env}) \quad (4)$$

In the coupled simulation, EnergyPlus uses the CitySim supplied equivalent $h_{r,env}$ and T_{env} to calculate weighted $h_{r,sky}$, $h_{r,grd}$, and $h_{r,air}$ values using the view factors and the sky-to-air split ratio. Figure 4 illustrates the schematic differences between the solo and coupled simulations on a theoretical example of a target building with two adjacent buildings with surfaces available for radiation exchange.

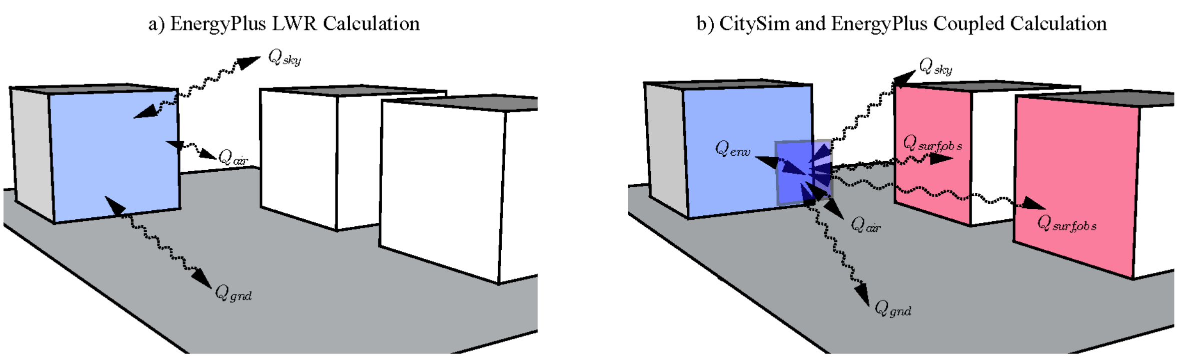

Figure 4. Comparison of the LWR components between a) Solo EnergyPlus and b) Coupled CitySim/EnergyPlus configuration ~~(?)~~ (Miller et al. 2015)

2.4. *Work flow automation*

The coupling, simulation and co-simulation process is completely managed within a program called VisTrails ~~(?)~~(VisTrails 2014). The implementation of this type of ~~workflow~~ work flow is outlined in previous work focused on automating DPV using the Kepler platform ~~(?)~~(Thomas and Schlueter 2012). This process reduces the effort expended by a designer down to pressing a single button. This functionality allows an iterative design style informed by readily available simulation results. An automated ~~workflow ties~~ work flow to tie the various steps together and ~~maintains~~ maintain the effortless iterative design process. VisTrails enables the coupling of various ~~workflow~~ work flow subprocesses script initializations, executions of the engines, and the compilation of the outputs. This tool empowers the coupling of ~~multiple~~ various executable files and their connecting scripts in graphical diagrams that ~~enhance~~ enhances reproducibility and process automation ~~(?)~~(Freire et al. 2014). The VisTrails ~~workflow~~ work flow diagram for the first case study in this paper is seen in Figure 5.

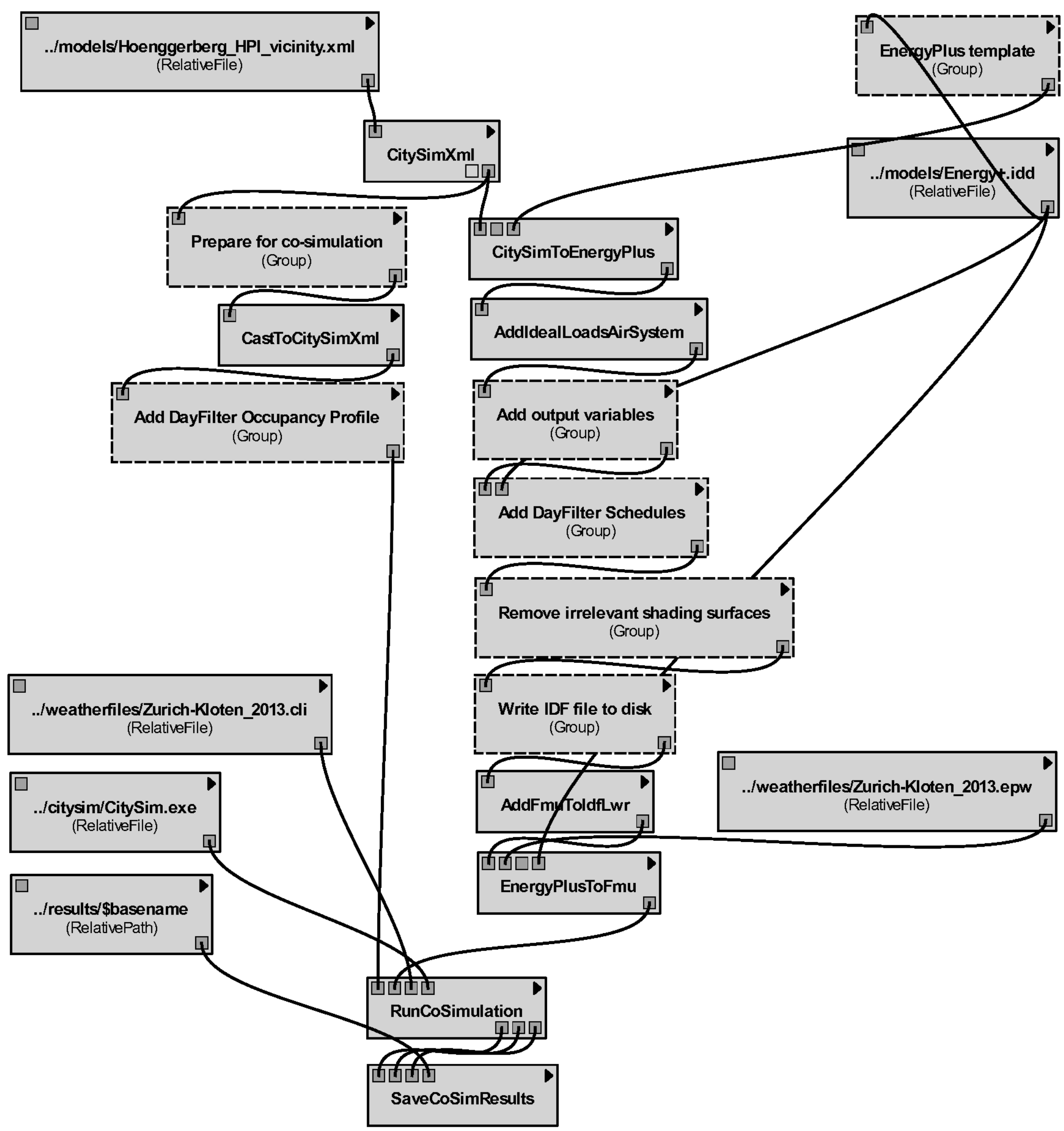

Figure 5. Workflow in VizTrails

2.5. *Simplified calibration*

In the first case study, one aspect of this analysis is the comparison of ~~the~~ actual measured performance of the target building on campus with the simulation results of the co-simulation. A simplified calibration procedure is adapted from previous research to compare the measured heating and cooling data available on campus with various simulation scenarios ~~(?)~~(Samuelson, Ghorayshi, and Reinhart 2015). This calibration procedure was utilized in the performance reconciliation of 18 buildings that were built according to the LEED Canada protocol and were under review of actualized performance. This protocol is unique in its analysis process to uncover design model deficiencies in a step-wise manner, utilizing the most ~~readily available~~ easily accessible knowledge first and working towards equilibrium between measured and simulated. There is an appropriate balance between the effort of implementation and value generated through the calibration process.

3. Implementation

The co-simulation process is implemented on two case studies in Switzerland. The first is the ETH Zürich Hoenggerberg campus in Zürich, Switzerland. The focus of this case study is to ~~quantify~~ compare the impact of the information exchange through co-simulation within the EnergyPlus engine. The intent on this campus was to develop techniques for retrofit analysis using EnergyPlus. The targeted building on this campus is the HPI Building. Raw measured data is available for many of the buildings on campus, thus a simplified calibration procedure is used to reconcile the simulation results.

The second case study is the EPFL campus in Lausanne, Switzerland. The targeted building, in this ~~instance~~case, was the Quartier Nord complex. The focus of this study was to compare the ~~solo and co-simulation~~ output results of ~~CitySim~~both CitySim and EnergyPlus. Reliable measured data for calibration is not currently available for this building.

3.1. *Campus case study 1: ETHZ Hoenggerberg Campus*

The ETH Zürich Hoenggerberg campus includes 32 higher education facilities with spaces allocated to laboratories, office space, lecture halls, cafeterias, data centers and other types of similar areas. The campus has a centralized energy management system (EMS) that contains 807 energy and water measurement points from heating, cooling, electricity, city gas, domestic hot water, ~~gray~~ grey water, and general water consumption.

The focus of the co-simulation process is that the performance of a targeted building is evaluated through solo and coupled methods. The HPI building on campus was chosen in this case study due to the amount and quality of measured data available from the EMS for this building. HPI is a 2,610 square meter building that is made up mostly of office space and classrooms. It also includes 400 m^2 convenience store and coffee shop. The building is indicated on a campus map shown in Figure 6 and is shaded red.

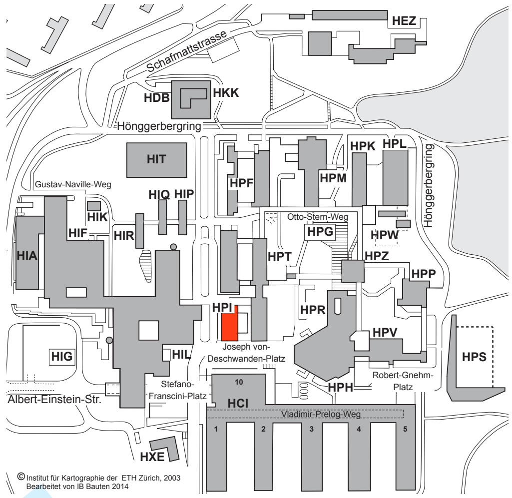

Figure 6. ETH Hoenggerberg campus map with the HPI building shaded red

3.2. *Model development*

In order to perform a co-simulation of the targeted buildings, initially a CitySim model of the campus was developed. Through the workflow automation process, this geometry was converted into an EnergyPlus input file as seen in Figure 7. The EnergyPlus input file was then used as an input to execute EnergyPlus solo and co-simulation processes for the purpose of simplified calibration, and then to understand the magnitude of ~~the~~ difference between these simulation scenarios.

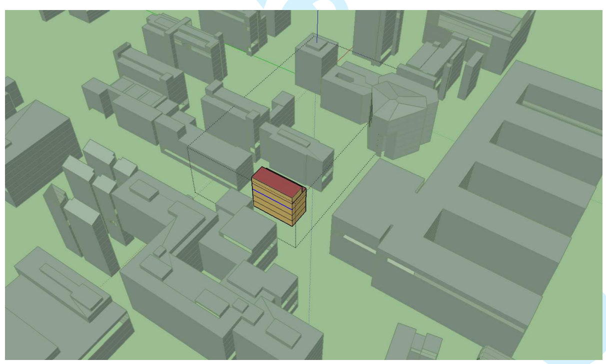

Figure 7. The HPI building ~~EnergyPlus model extracted from the CitySim model. The HPI building is seen as the light and dark brown building in the center surrounded by gray masses that represent other buildings on campus. The graphic is illustrated~~ modeled with OpenStudio for ~~Sketch-up.~~Sketchup

3.3. *Measured data collection and calibration*

Energy data from the HPI building was collected and analyzed in the context of the simplified calibration procedures. The measured datasets ~~were~~ are screened and aggregated into typical usage profiles to be used for the lighting, plug- loads, and HVAC equipment availability schedules and power densities. Figure 8 illustrates the aggregation examples of electrical energy for the HPI building. This profile was created through a filtering and clustering process known as *DayFilter* ~~(?). Cluster 0 represents the typical energy profile for Sunday, while Cluster 1 dominates the Saturdays of the data set. Clusters 2 and 3 make up most of the weekdays of the data set with Cluster 3 being more common in non-summer months. These profiles are~~ (Miller, Nagy, and Schlueter 2015). This profile is used to set the availability schedules as inputs into the EnergyPlus simulation to emulate the way occupants inhabit the building and how the building management system (BMS) controls the lighting and HVAC systems.

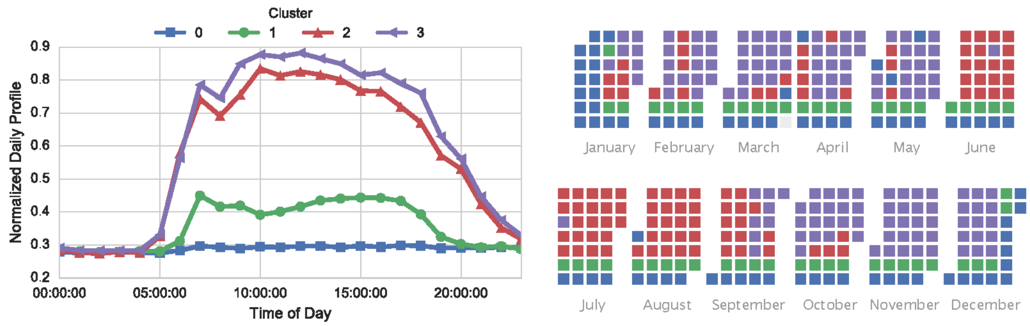

Figure 8. HPI Electrical Energy Typical ~~measured data electricity profiles of (left) average daily electrical consumption for each cluster and (right) color-coded calendar of which days fall within each cluster. The diagram on the right is each month of the year with each row corresponding with a day of the week (starting with Monday) and each column corresponding to a week of the month.~~Profiles

The measured and simulated data from both the co-simulation and EnergyPlus solo simulation ~~were analyzed~~ was compared in order to ~~understand how both the solo and co-simulations compare to real, measured data~~create a realistic scenario for comparison. The calibration process was undertaken through a series of steps such as including local weather conditions for the simulation period and adding custom lighting schedules and power densities extracted from the measured data. The models were calibrated to the summer season (May-September) for cooling and the winter season (Jan-April and October to December) for heating. This approach was taken as the data quality for the measurements were deemed most accurate during the appropriate seasons. Figure 9 illustrates a comparison of the measured data with the simulations after the tuning process. The final calibrated EnergyPlus solo model had a normalized mean bias error (NMBE) of -9.36% and a coefficient of variation of root mean square error (CVRMSE) of 21.7% for cooling and ~~5.02~~-9.36% and 29.4% for heating. These metrics fall within the +/-10% NMBE and +/-30% CVRSME used in this case study for calibration. ~~A total of 37 calibration iterations were undertaken to modulate the simulation results to within these criteria.~~ The goal of calibration, in this case, is to just bring the models to within a reasonable range of reality in order to bring more confidence to analysis of the discrepancies between the solo and co-simulation scenarios.

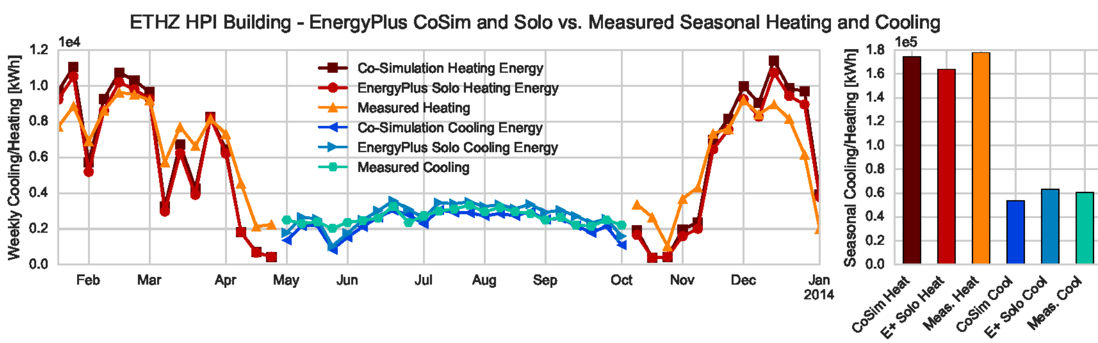

Figure 9. HPI Measured vs. Co-Simulation and EnergyPlus Solo for Heating and Cooling Seasons

3.4. *EnergyPlus co-simulation results*

After calibration, a comparison of co-simulation and solo EnergyPlus simulations is made. For cooling, a discrepancy can be seen between co- simulation and solo EnergyPlus. Co-simulation decreases the predicted cooling energy by 15.5%, as seen in Figure 10. Figure 11 illustrates the difference in predicted heating energy consumption across the test year. A consistent offset exists across the time frame of days in January, the peak of the heating season. A more varied discrepancy across the heating months is noticed resulting an overall increase of heating prediction of 6.5% due to co-simulation. The exchange of ~~long-wave~~ long wave radiation for this particular site is substantial due to the proximity of surrounding buildings. These performance differences due to co-simulation are compared to a theoretical single-zone case study in which there was a 15-30% increase in heating energy and a 4-11% decrease in cooling energy (Miller et al. 2015). The results from this case study are less extreme on the heating side and more on the cooling side than the theoretical case study.

When comparing the solo and co-simulated models to the measured data, it is noticed that cooling energy is over-predicted by the solo simulation by 4%, while co-simulation under-predicted by 11.1%. ~~This discrepancy is likely due to a loss in long-wave radiation in the co-simulation to the surrounding buildings, thus reducing the overall cooling load.~~

For heating energy, co-simulation was able to bring the predicted value to within 2% of the measured value for the year, an improvement as compared to the solo simulation, which was 8.5% less than the measured value.

~~This situation is also likely due to the long-wave radiation loss to surrounding buildings, thus increasing the overall heating load.~~

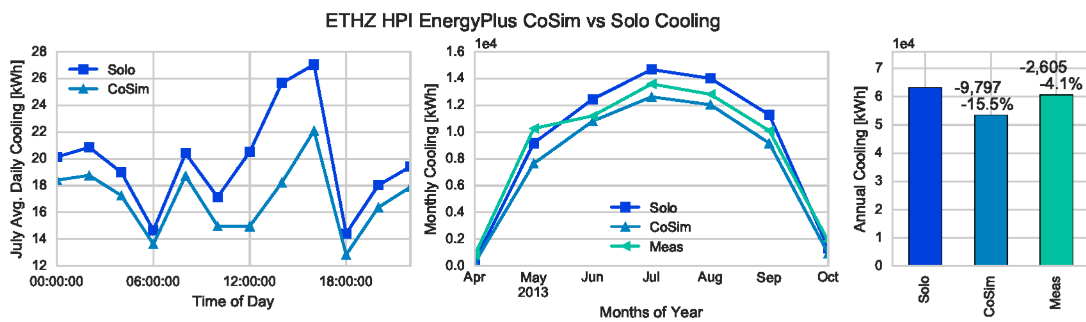

Figure 10. HPI Co-Simulation vs. EnergyPlus Solo for Cooling

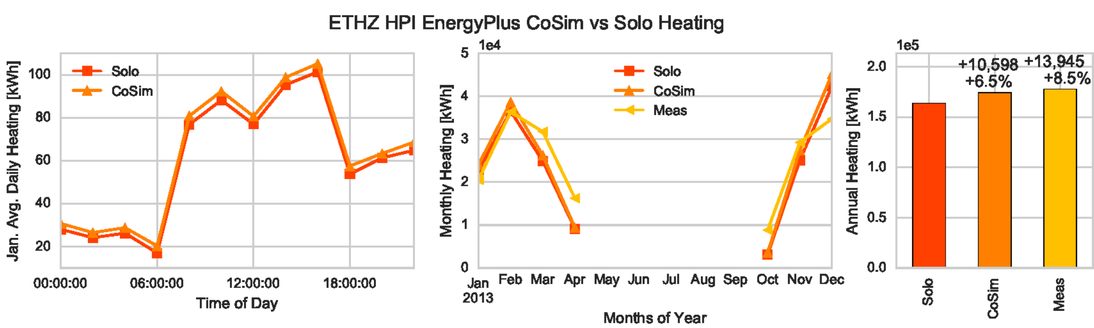

Figure 11. HPI Co-Simulation vs. EnergyPlus Solo for Heating

3.5. *Campus case study 2: EPFL Quartier Nord*

Quartier Nord is a whole new quarter of the École Polytechnique Fédérale de Lausanne (EPFL) campus located at its northwest corner. This complex includes a Convention Centre with an auditorium with a maximum capacity of 3000 (seated) people, housing for 516 students, retail and service areas and a hotel. As a public space, this ensemble is organized around the central plaza as seen in

Figure 12). With a particularly strong visual and formal identity, the SwissTech Convention Centre (STCC) is clearly the key protagonist. Designed as a Minergie building, it includes modern energy conversion technologies to reduce its energy consumption. The focus of the co-simulation is realized on the STCC, simulated with the nearby buildings for housing, retail and service areas~~(?)~~.

Figure 12. The Quartier Nord at EPFL in Lausanne

3.6. *Model development*

The information required in the simulation mainly comprises three parts: physical, geometrical and operational data. The geometry information including the shape, dimension, structure and materials was obtained from the Real Estate and Infrastructure Department of École Polytechnique Fédérale de Lausanne (EPFL), which was responsible for carrying out the project from call to tender to construction. However, since the documents provided were full of details but also conflicting with what has been installed as compared to the documents before construction, the task to realize a precise model of the buildings itself is rather tedious. Besides, it is even more challenging to get the operational data (daily occupancy, lighting, and electrical equipment usage level and ventilation rate) as the building has only recently been set in operation mode and as engineers and technicians have been working on improving the controls. Therefore, due to unreliable monitoring data, the calibration step of the model was not undertaken.

Considering the lack of detailed information about the building, a so-called detailed reference case was modeled with EnergyPlus ~~(?)~~ (Mauree et al. 2015) in which regulation standards applied in the design phase from the ~~local building code~~ SIA norms were used to complete the missing information. A rendering of this model is seen in Figure 13.

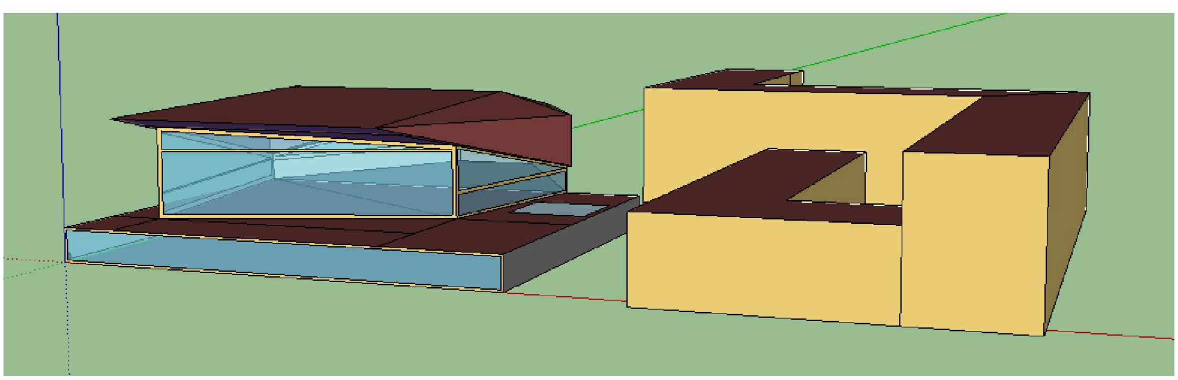

Figure 13. The Quartier Nord modeled with OpenStudio for Sketchup[2]. The STCC on the left is the main focus of the study and is represented by two thermal zones.

The corresponding CitySim model was created by exporting a DXF file from EnergyPlus~~for the~~

~~whole of Quartier Nord~~, and importing it into the Graphical User Interface of CitySim. Physical characteristics of the building were added to complete the CitySim model. Finally, the same script as described in Section 2 was used to export the model from CitySim to EnergyPlus, giving a simplified EnergyPlus model.

3.7. *Comparison of EnergyPlus and CitySim*

Both the CitySim and EnergyPlus engines are utilized in this case study. The first comparison to observe is the differences between the two engines when focused on the ~~STCC~~ Quartier Nord building. When simulated in isolation, the CitySim engine predicts a 28.6% increase in heating load and a 44.4% increase in cooling load as compared to EnergyPlus. This phenomenon is due to the differences in the way each of these engines calculates heating and cooling loads. ~~CitySim has a much more simplified model of building occupants, lighting, and plug loads. CitySim also includes long-wave radiation exchange calculations that can greatly influence the heating and cooling load calculations as well.~~ Use of the co-simulation process brings the engines to within 5.4%. Figure 14 illustrates these differences for cooling and Figure 15 for heating.

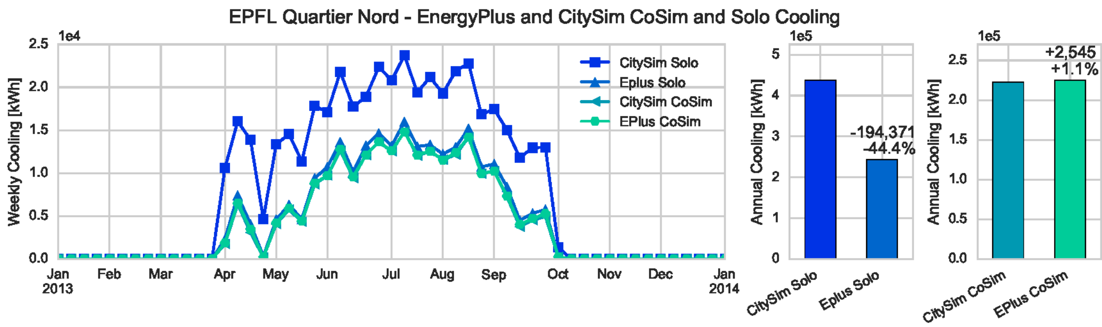

Figure 14. ~~STCC~~ Quartier Nord CitySim vs. EnergyPlus Solo for Cooling

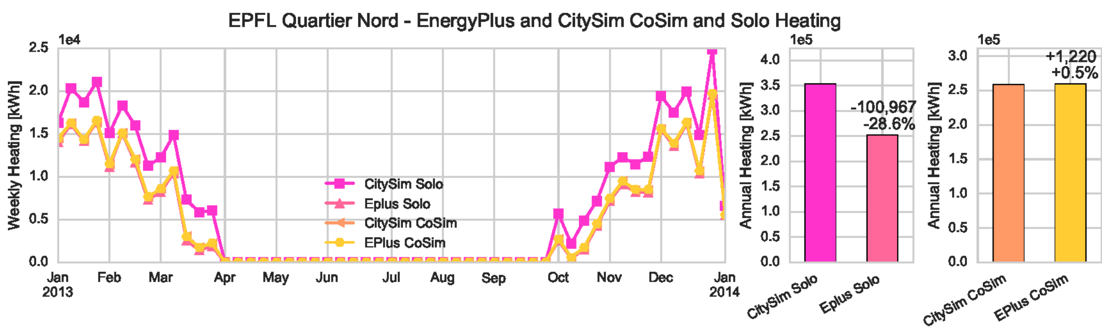

Figure 15. ~~STCC~~ Quartier Nord CitySim vs. EnergyPlus Solo for Heating

3.8. *EnergyPlus co-simulation results*

The ~~STCC~~ Quartier Nord building is also simulated within the solo and ~~co-simulation~~ cosimulation environments. When focusing on the EnergyPlus results, a 7.5% decrease in cooling energy is observed, as seen in Figure 16. A 2.8% increase in heating energy is observed, as seen in Figure 17. These differences are less pronounced than the HPI and theoretical case studies due to the number and proximity of surrounding buildings is not as large. ~~long-wave~~ Long wave radiation exchange in this situation doesn't have as large of an impact on the heating and cooling calculations.

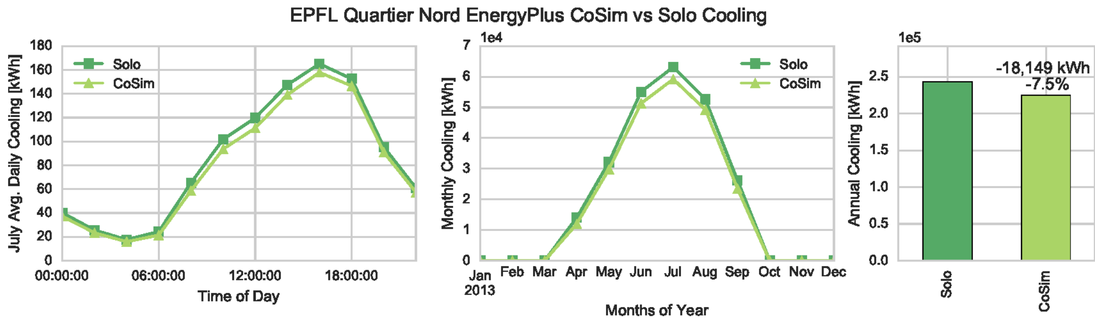

Figure 16. Quartier Nord EnergyPlus Co-Simulation vs. Solo for Cooling

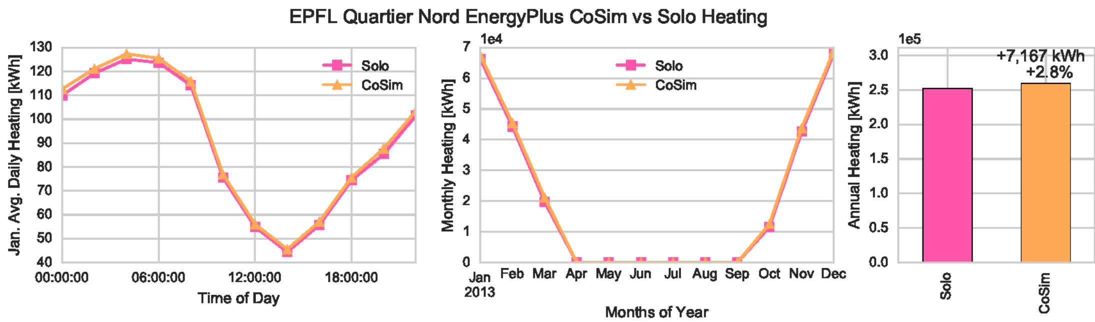

Figure 17. Quartier Nord EnergyPlus Co-Simulation vs. Solo for Heating

~~One of the key insights in this work is that each of the engines is enabled to account for the various physical phenomenon in their simulation process that were previously impossible. For example, through co-simulation, EnergyPlus was able to utilize the long-wave radiation exchange capabilities of CitySim. The Conclusion]DiscussionTwo campus case studies were presented in this paper to showcase a unique process of extracting model meta-data, conversion of those data into input files for two separate simulation engines, and the solo and co-simulation process of those engines on two real-world case studies. The analysis of the results shows that for the first case study, co-simulation can achieve values closer to measured reality for heating, but not cooling. These results are unique to this case study and simply show that the co-simulation process may be helpful for heating only in this particular instance. A limitation of this study is that we only analyze a single building against measured data in this context. In the second case study, significant discrepancies are found between the CitySim and EnergyPlus engines which were corrected using the co-simulation process.~~

~~One of the key insights in this work is that each of the engines is enabled to account for the various physical phenomenon in their simulation process that were previously impossible. For example, through co-simulation, EnergyPlus was able to utilize the long-wave radiation exchange capabilities of CitySim. The~~ Conclusion The ability to couple and leverage the best aspects of multiple simulation engines can enhance the modeling of ~~large-scale~~ large scale urban agglomerations.

~~Disadvantages of the co-simulation process are mainly centered upon the increase in computing time and power needed for the FMI to coordinate data exchange between the two simulation engines. After calibration, a comparison of the run-times of the co-simulation and solo EnergyPlus simulations show that the execution time for the solo EnergyPlus simulation was 1 minute and 49 seconds compared to 28 minutes and 10 seconds for the co-simulation.~~

4. ~~Conclusion~~

~~This paper outlines the implementation of~~ This paper has outlined two such scenarios in which the building-focused EnergyPlus simulation engine is coupled and co-simulated with the urban-scale CitySim engine. This process is implemented through a fully automated ~~workflow~~ work flow process that extracts geometry information at the urban-scale, creates the necessary input information, executes each engine with information exchange at each time step of targeted variables, and accumulates the results of ~~the~~ analysis. The process has been implemented on simplified theoretical scenarios in the past ~~,~~ and the key innovation with this work is in implementation on actual case study campuses and targeted buildings. The results illustrate that the differences between the co- simulation and solo environments are within range of previous theoretical models. The results show that there is a noticeable impact More reliable results of the magnitude of differences between the simulation techniques can be extracted from these real-world scenarios.

Future work in using co-simulation models for buildings and campuses would more intensively utilize the model results in a practical implementation of retrofit scenarios or urban-scale energy systems research.

~~More implementations would also test the feasibility of using co-simulation for retrofit analysis, urban planning studies, and cooling and heating system optimization.~~

3.1. ~~*Acknowledgments*~~ *Acknowledgements*

The authors would like to acknowledge the ETH Zürich Campus Facilities Department, the EPFL Real Estate and Infrastructure Department, and Emanuel Thoma for their assistance in this project. This research was funded by the Competence Center in Energy and Mobility (CCEM) under the Urban Multi-scale Energy Modeling (UMEM) project.

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Ian Beausoleil-Morrison
Jan Hensen
Co-Editors
Journal of Building Performance Simulation

Singapore, December 19, 2016

Journal Paper Submission

Dear Dr. Beausoleil-Morrison and Dr. Hensen:

The attached manuscript entitled “Urban and building multiscale co-simulation: case study implementations on two university campuses” is an original research article that I would like to submit for consideration in Journal of Building Performance Simulation. This paper outlines the process of co-simulation between EnergyPlus and CitySim for two campuses. This paper builds upon the work from two previous conference papers and includes properly-referenced content from both papers. References of those papers are found below:

Thomas, D., Miller, C., Kämpf, J., Schlueter, A., 2014. Multiscale co-simulation of EnergyPlus and CitySim models derived from a building information model, in: Proceedings of Bausim 2014: Fifth German-Austrian IBPSA Conference. Presented at the Bausim 2014: Fifth German-Austrian IBPSA Conference, IBPSA, Aachen, Germany, pp. 469–476. doi:10.13140/2.1.4639.1040

Miller, C., Thomas, D., Kämpf, J., Schlueter, A., 2015. Long wave radiation exchange for urban scale modelling within a co-simulation environment, in: Proceedings of CISBAT 2015. Presented at the CISBAT 2015, CISBAT, Lausanne, Switzerland, pp. 871–876. doi:10.13140/RG.2.1.2876.4640

This paper builds upon the previous research by applying the workflow to two campus case study projects. This contextual application gives a realistic analysis of how much differences between solo and co-simulations.

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Any questions or comments can be directed to myself as the corresponding author. I am available via email at miller.clayton@arch.ethz.ch and by phone at 1-402-403-0090.

Kind Regards,

Clayton Miller