MULTISCALE CO-SIMULATION OF ENERGYPLUS AND CITYSIM MODELS DERIVED FROM A BUILDING INFORMATION MODEL

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ABSTRACT

We present an approach for rapidly assessing the performance of early design stage building information models (BIM) from both the building and urban systems scale. This effort builds upon two previously developed tools, the Design Performance Viewer (DPV) and the CitySim urban simulation engine. It couples them to produce a more informed model. The DPV is a plugin for Autodesk Revit Architecture that creates a model for the EnergyPlus building performance engine based on information contained in the BIM. We combine the two simulation engines using the Functional Mock-up Interface (FMI) co-simulation framework to improve the accuracy of both simulations. This work extends the DPV to extract a CitySim model in addition to the EnergyPlus model. The CitySim model contains not only the building being investigated, but also a simplified representation of the surrounding buildings. We extend the CitySim solver to use the FMI standard for co-simulation to exchange simulation variables with the EnergyPlus model at each time step. This process includes an automated workflow that enables simulation driven design employing these techniques. We compare the results of the coupled and uncoupled simulations and explain discrepancies. We then discuss further refinements to the models such as more accurate representation of the long wave radiation exchange.

INTRODUCTION

Building performance simulation is a mature field of research with numerous available simulation engines and system modeling capabilities. A major example is the EnergyPlus simulation program (Lawrie et al., 2001). Urban scale energy modeling is an emerging field that seeks to model multiple collections of buildings and the surrounding urban micro-climate. The interaction between the building and urban scale has been shown to influence the prediction of performance on both scales. For example, the urban micro-climate present in street canyons has been modeled to show higher surface temperatures leading to higher cooling loads within the building systems simulation (Allegrini et al., 2012). Empirical data collected in London (Kolokotroni et al., 2012) and Athens (Santamouris et al., 2001) reinforce these findings.

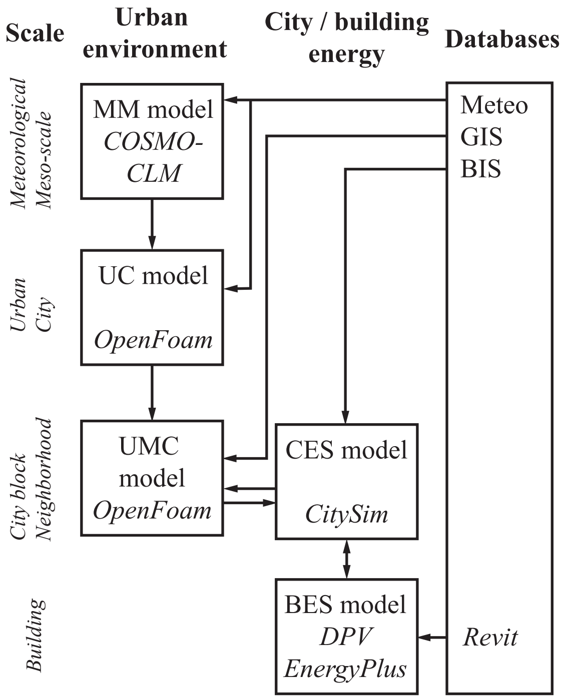

Figure 1: EnergyPlus and CitySim coupling are part of the wider context of the UMEM project. Each block in the diagram represents an environment, with the tool/engine name in italics (adapted from (Dorer et al., 2013))

This evidence motivates the need to couple building and urban simulation. This intent has fostered previous attempts of information exchange between EnergyPlus and the TEP Urban Canopy Model program (Bueno et al., 2011) and ENVI-met, a micro-climate computational fluid dynamics (CFD) program (Yang et al., 2012).

This paper is part of the Urban Multiscale Energy Modeling (UMEM) project, in which models of different scales are connected and co-simulated to create a more comprehensive analysis of the urban scale (Dorer et al., 2013). We focus on the computational interface between the building energy model, using EnergyPlus, and the urban energy model using CitySim. The UMEM project overview is shown in Figure 1 and the context of the coupling task is shown as the interface between the City Energy Simulation (CES) model and the Building Energy Simulation (BES) model. CitySim is an urban performance simulation engine that comprises a Solver and a Designer (the 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. To achieve a good compromise between modeling accuracy, computational overheads and data availability, CitySim simulates multiple buildings up to city scale using simplified models. As an example, each building's thermal behavior is based on an electrical analogy using a two node resistor-capacitor network.

The Design Performance Viewer (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 main philosophy behind the tool is rapid simulation of the building information model from the earliest design possible 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 existing 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. Since part of the scope of the UMEM project includes coupling a micro-climate simulation with the CitySim software, we couple the weather input to EnergyPlus with CitySim. In return, CitySim receives a more precise simulation of the building's thermal behavior and associated surface temperatures which can be used for the long wave radiation exchange. Additionally, with coupling we can also make use of a more sophisticated stochastic model for occupation present in CitySim (Haldi and Robinson, 2011).

This paper first outlines this coupling and workflow automation process by describing the sub-steps e.g., BIM data extraction, EnergyPlus and CitySim input file creation, the use of the Functional Mock-up Interface (FMI), and workflow automation. The schematic of this process can be seen in Figure 2. These steps are performed on a simplified example of a small target building surrounded by other buildings in an urban setting. The results of preliminary co-simulations with this model are presented with challenges encountered as well as future work to be completed.

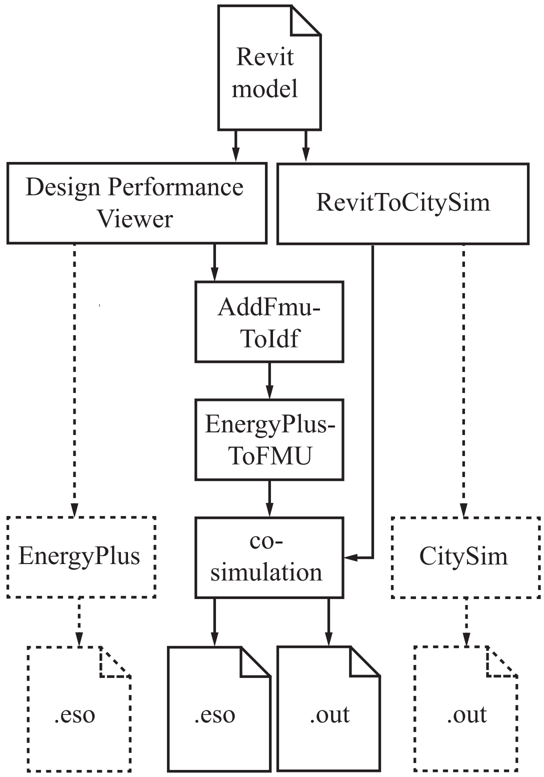

Figure 2: Overview diagram of the coupling process including tools and outputs

COUPLING PROCESS

This section outlines the EnergyPlus/CitySim coupling process starting from the building information model (BIM) to the output of results from a co-simulation. In order to illustrate this process, we created a simplified scenario model in Revit that will be used to simulate and compare the results from three scenarios:

1. EnergyPlus simulation of the target building with the surrounding buildings modeled as EnergyPlus shading objects
2. CitySim simulation of the entire urban energy environment using the CitySim thermal models to simulate the target building
3. Coupled EnergyPlus/CitySim simulation in which certain variables are exchanged at each timestep as described in this section

Figure 3 visualizes this simplified scenario with the target building shown in the center as a single-zone, one-story building surrounded by four larger mass objects that represent the urban environment. The coupling procedure is broken up into various subprocesses. First, we extract an EnergyPlus model from the BIM using the Design Performance Viewer. Next, we bundle the EnergyPlus model into an FMU (Functional Mock-up Unit) ready for co-simulation. We extract a CitySim model from the BIM by applying default values for unknown details producing a low-resolution model of the building's neighborhood.

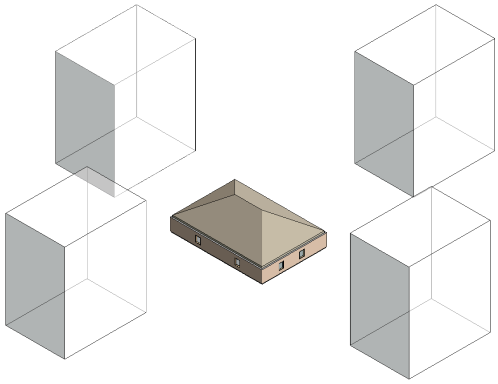

Figure 3: The BIM model of the example simplified target building with surrounding mass objects

Finally, we co-simulate the two simulation models and display the results to the user. This section will cover each of these steps in detail.

BIM to EnergyPlus extraction

We use the DPV 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 DPV uses the layering and materials of the construction types, enhancing them with physical attributes relevant to EnergyPlus. Where not defined, the DPV assumes default values.

The DPV uses the EnergyPlus Ideal Loads HVAC system to model the supply side of the building's systems. A simple dual set point is used to keep the building in homeostasis. The different heating and cooling systems used by the DPV are implemented with simple formulas based on the yearly heating and cooling loads. The DPV extracts an internal model of the BIM, designed to contain only information necessary for energy simulation. A final stage of the extraction process exports the internal model into the IDF format used as input to the EnergyPlus simulation engine. Figure 4 shows a schematic of the process.

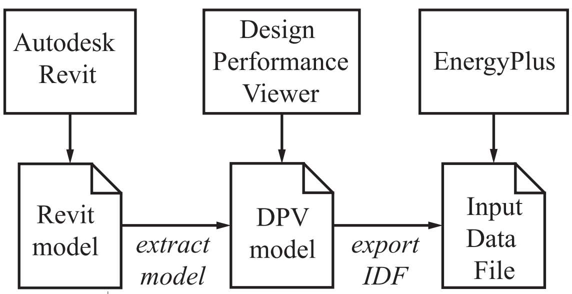

Figure 4: Data transformations performed by DPV from BIM to IDF for EnergyPlus

BIM to CitySim scene extraction

Next, we create geometry to be used in both the CitySim and EnergyPlus models as buildings and surfaces surrounding the building targeted in the IDF. We use a feature of the DPV 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. We add a transformation on 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.

Table 1: Default values for CitySim model

TAG	ATTRIBUTE	VALUE
Building	Ninf Simulate Tmax Tmin	$0.4\ h^{-1}$ TRUE 26 °C 20 °C
Building/ HeatTank	Cp Tmax Tmin V Brand Model	$4180\ J/(kg\cdot K)$ 35 °C 20 °C $0.01\ m^3$ Rack RTB-25
Building/ CoolTank	Cp Tmax Tmin V phi rho brand model	$4180\ J/(kg\cdot K)$ 20 °C 5 °C $0.01\ m^3$ 20 W/K $1000\ kg/m^3$ Unknown Unknown
Building/ HeatSource	beginDay endDay	258 151
Building/ HeatSource/ Boiler	Pmax Brand nth fuelID Model	1.00E+12 W PARKER 0.95 1 T300L
Building/ Zone	GroundFloor Psi	TRUE 0.3 W/K
Building/ Zone/Wall	Glazing-GValue GlazingRatio Glazing-U-Value Openable-Ratio ShortWave-Reflectance type	0.5 0.5 $1.3\ W/(m^2K)$ 0.5 0.2 Default
Building/ Zone/Roof	Glazing-GValue GlazingRatio Glazing-U-Value Operable-Ratio type	0 0 0 0 Default roof
Building/ Zone/Floor	type	Default floor

Table 2: Default wall / floor / roof type properties

Property	Value
Conductivity	$0.47\ \mathrm{W/(m \cdot K)}$
Cp	$900\ \mathrm{J/(kg \cdot K)}$
Density	$1600\ \mathrm{kg/m^2}$
Thickness	0.5 m

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. We group the shading surfaces into buildings based on the mass object they were extracted from. These 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. We also apply a default heating and cooling system and other properties needed by the CitySim solver.

The CitySim scene is written to a file in the XML format used by CitySim. We enrich the XML format with attributes relating geometry back to the elements in the BIM model so that we can compare simulation results between the two simulation engines. Tables 1 and 2 show the default input values in the CitySim input file to give an indication of the basic inputs for that engine. We also mark the main building with a special value for the CitySim *Simulate* attribute. In addition to the values *true* and *false*, we add a value *ep*, for *EnergyPlus*, that requires an additional attribute *fmu* to specify the path to the Functional Mock-up Unit used in the co-simulation.

IDF file augmentation

As of version 8.1.0, EnergyPlus supports exporting a simulation model as a Functional Mock-up Unit (FMU) (Nouidui et al., 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. We have found that in order to export an output variable using the FMU export functionality, the variable itself must also be output with an IDF object of type *Output:Variable* or *EnergyManagementSystem:OutputVariable* in the IDF file as well.

Since the model used by CitySim to simulate a building is more abstract than the model used by EnergyPlus, we use the EMS to aggregate certain values. CitySim does not model windows separately, so we calculate a weighted average of window and wall surface temperatures with EMS subroutines.

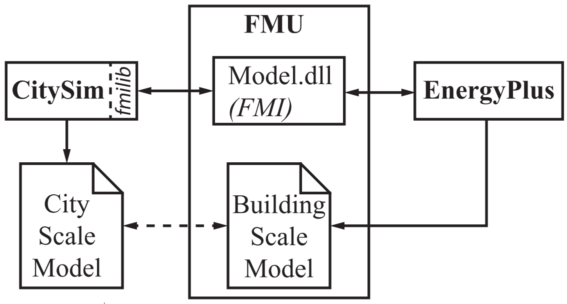

Figure 5: Simulation information exchange between CitySim and EnergyPlus using FMI

We automate the process of augmenting the IDF file with the EMS subroutines and FMU export objects. The script *addfmutoidf.py*, written in the Python programming language, uses the *parseidf* module to read in the IDF file and add the new IDF objects based on those found in the model. This script reads in the list of surfaces defined in the IDF file and produces EMS scripts to aggregate and output the surface temperatures of the wall and the windows as well as any other output objects necessary.

FMU creation process

The FMU creation process is the basis for coupling the two models at each timestep in the simulation. Figure 5 illustrates this process from both the EnergyPlus and CitySim perspective. We feed the augmented IDF file to the *EnergyPlusToFMI* script (Nouidui and Wetter, 2014). This script requires a *C* compiler and linker. We use Microsoft Visual Studio 12, which is not one of the defaults shipped with the script so we needed to edit the scripts *compile-c.bat* and *link-c-exe.bat* to use the correct path to compiler and linker respectively.

Once configured, the EnergyPlusToFMI 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. Table 3 and 4 outline the variables exchanged between EnergyPlus and CitySim through the FMI. We used the *fmilib* library from the JModelica project to test the FMU produced (JModelica, 2014). We altered one of the sample programs (*fmi_import_cs_test.c*) to load the FMU, run it and print out the values exported from EnergyPlus. This code was then used as a guide to extending the CitySim solver to load FMUs for co-simulation.

Adaption of CitySim

We recompiled the JModelica *fmilib* using MinGW to provide a dynamic library that is compatible with CitySim. As a first approach, only the debug version of CitySim Solver (named CitySimd) was linked to the FMI library as this version is not parallelized. Within CitySim, the simulation loop begins by an initialization of the FMI slave, which starts up EnergyPlus and does the warm up of the building.

Table 3: Values imported by EnergyPlus from CitySim by the FMU

Object (ep_id)	**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)
Zone	Occupation	Fraction of the maximum occupation (0.0-1.0) overrides the EnergyPlus occupation schedule with the CitySim stochastic schedule.

On an hourly basis, CitySim performs a heating and cooling needs prediction step. We replaced the temperature determination step for the main building with the results of the EnergyPlus timestep as obtained through FMI library. We use the FMI library to send climatic and occupational data from CitySim to EnergyPlus (see Table 3), and to receive data from EnergyPlus that are further used within CitySim for the next time steps (see Table 4).

Weather file generation

In order to compare the augmented simulation with the original EnergyPlus-only simulation, we need to run both simulations with the same weather data. The Design Performance Viewer already comes with a library of weather files for different locations. These weather files are based on the EnergyPlus weather file format, *.epw*. This format is flexible and contains a lot of information about the weather being described. CitySim uses a more simplified format, *.cli*, that contains a subset of the information in *.epw* files. We utilized the Meteonorm software to create the default weather data files for both simulation engines with the exact same input information (Remund et al., 2014). We have plans to automate this process of *.epw* and *.cli* file creation through a Python script which can be inserted into the entire workflow.

Table 4: Values exported by EnergyPlus to CitySim by the FMU

Object (ep_id)	**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. This respects the temperatures of the windows on the wall, weighted by area.
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)

Workflow automation

The insight that simulation data has the most impact early on in the design process inspired the development of the original DPV plugin. This philosophy is outlined in previous work focused on automating DPV workflows using the Kepler platform (Thomas and Schlueter, 2012). These efforts reduce 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. We implemented an automated workflow to tie the various steps together and maintain the effortless iterative design process. We use the VisTrails software to design and implement the automated workflow (VisTrails, 2014). VisTrails enables the coupling of various workflow subprocesses script initializations, executions of the engines, and the compilation of the outputs. VisTrails also creates an environment in which the automated workflow is easily reproducible, resulting in better dissemination of the process (Freire et al., 2014). The process in VisTrails is seen in Figure 6. The highest level includes the extraction of both the EnergyPlus and CitySim information from the BIM. The second stage focuses on preprocessing the IDF file for the purpose of co-simulation. The third stage executes the simulation engines for the three scenarios and the last phase stores the simulation output for further analysis.

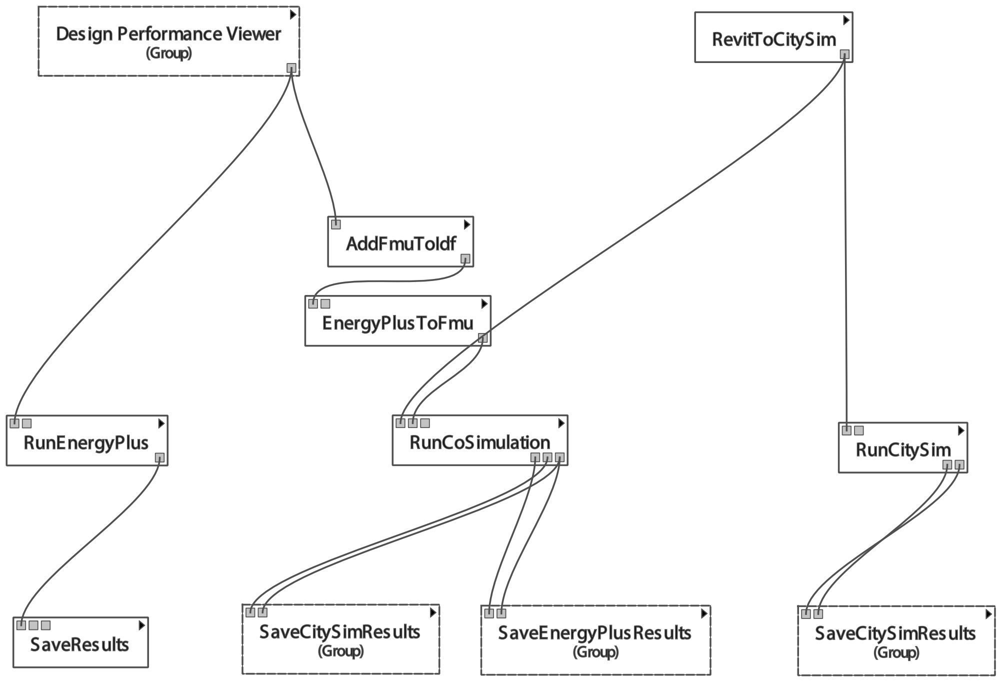

Figure 6: Workflow automation as it's presented in VisTrails as a block diagram. Each block executes a certain part of the simulation coupling process.

INITIAL RESULTS AND DISCUSSION

The three scenarios outlined in the process section were simulated using the simplified model and the results are presented in this section. The main goal of these initial results is to visualize and understand the differences that the coupling process achieves in both EnergyPlus and CitySim in the heating and cooling load calculations. We tried to match the EnergyPlus inputs as closely as possible to the default CitySim inputs outlined in Table 1 and 2. This matching was done in order to create a valid comparison between coupled and uncoupled scenarios. These simulation results can be seen in Figure 7. The following subsections will discuss discrepancies between coupled and uncoupled for each model type, plans for investigation of the causes, and future work to be done to improve accuracy of the coupling process.

EnergyPlus coupled vs. uncoupled

There are slight differences in the EnergyPlus coupled vs. uncoupled heating and cooling load calculations as seen in Figure 7a and 7b. These discrepancies are currently under investigation and may be attributed to definitions of the diffuse solar and direct solar, the wind direction definition differences between the two tools, and the occupation schedule, which we take from CitySim's occupation fraction schedule. The fact that the EnergyPlus engine is performing the load calculation for both scenarios is the driver behind the small magnitude of differences in results. CitySim is simply slightly influencing the existing heat balance calculation through contribution of environmental variables.

Two additional coupling enhancements are currently underway that will increase the influence CitySim has on the EnergyPlus engine. The first is a coupling of the long wave radiation (LWR) exchange between the buildings in the urban area being simulated. The LWR exchange between surfaces is computed in CitySim by a linearization of the longwave energy balance at each surface around an average between the surface and its environmental temperatures. The environmental temperature for each surface is determined using the simplified radiation algorithm neglecting inter-reflections. In EnergyPlus, the longwave calculation does not have access to the environmental temperature and therefore further research is necessary to couple the longwave models of both engines. We plan to implement a LWR exchange process based on work done on a simplified process using the EnergyPlus EMS features and input schedules (Evins et al., 2014).

The second major enhancement is the process related to more closely coupling localized micro-climate weather data into the EnergyPlus engine. These values will come from specific urban micro-climate models which can create customized weather information for each building in the urban simulation. This effort would increase the accuracy of weather data that influences systems performance and comfort.

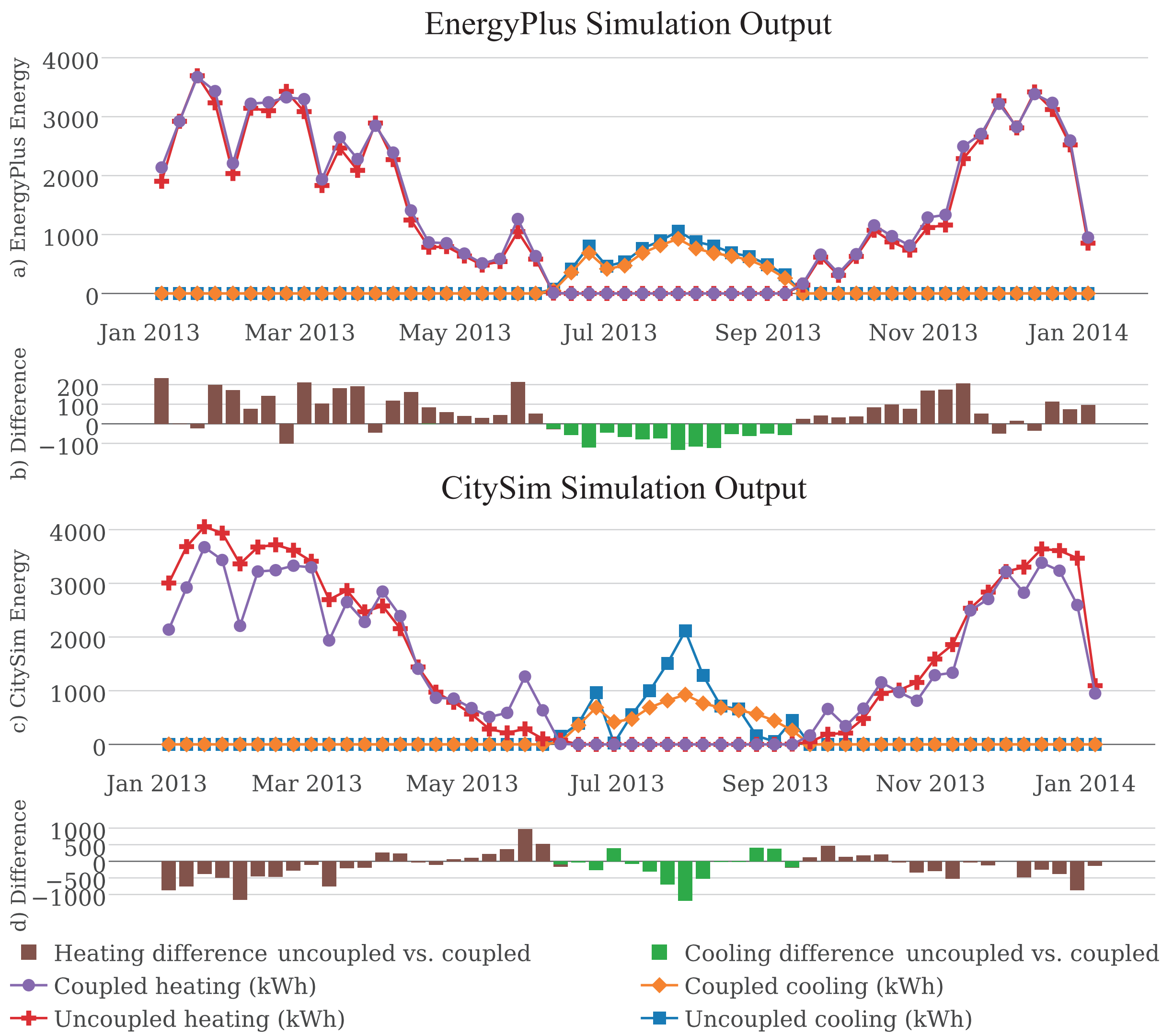

Figure 7: Comparison of weekly energy output totals (in kWh) from simulation runs of uncoupled vs. coupled simulations for both EnergyPlus and CitySim. Heating and cooling differences are calculated as coupled minus uncoupled outputs. Note that the Difference y-axis scales (b and d) are different.

CitySim coupled vs. uncoupled

Comparison of the CitySim coupled versus uncoupled simulations shows a much larger discrepancy in the cooling and heating loads as compared to the EnergyPlus scenarios. The comparison is seen in Figure 7c and 7d. A major reason for the magnitude difference is due to the fact that EnergyPlus is overwriting the CitySim building load calculations in the coupled version. Thus, there are many more model and variable input differences to reconcile when comparing two different simulation engines in order to see a close match. There is a significant difference in detail and resolution in which different loads inputs can be specified within CitySim as compared to EnergyPlus. For example, the lighting and equipment power densities can be finely specified in numerous configurations in EnergyPlus while CitySim treats them a simple correlation with occupancy. Another difficult challenge was to create similar inputs for ventilation for the two engines. EnergyPlus has a library of possible ventilation strategies while CitySim treats ventilation with a simplified formula. These facts lend themselves to the motivation for coupling the models in the first place; EnergyPlus is designed to perform detailed building load calculations, while CitySim is designed for the urban weather environment.

CONCLUSION

This paper has outlined a process of coupling the EnergyPlus and CitySim simulation engines based on information extracted from a building information model (BIM). This work was a proof of concept in utilization of a chain of existing tools and features including Revit, the DPV, and the new FMU export functionality of EnergyPlus. CitySim was extended to provide FMU import functionality. The performance outputs showed a close correlation between the coupled and uncoupled EnergyPlus simulation, while there was a larger discrepancy between the CitySim results. The discussion of these discrepancies motivates future enhancements in the coupling process including long wave radiation (LWR) exchange and microclimate weather inputs. The process also revealed the strengths and weaknesses of each engine, reinforcing the motivation for coupling them in this context.

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