KTH Industrial Engineering
and Management

Demonstrating the significance of microclimate on annual building energy simulations using RadTherm

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Abstract

Buildings account for over 35% of the energy demand in OECD countries, making them a prime target for improvement. (EIA 2011) To help building owners reduce energy usage, ratings systems such as LEED have been developed. A prerequisite for certification is the demonstration of energy efficiency through computer modeling; however, the complex nature of building energy simulations too often leads to errors of up to 30% (Turner and Frankel 2008). One source of significant error can be the assumptions made of environmental conditions, which are often simplified to speed up simulations.

To demonstrate the significance of active microclimate modeling, a building energy model combined with a microclimate model has been created in RadTherm, a commercial CAE thermal solver. Simulations are run using Passive House construction in three types of environments, and demonstrate an increase in energy demand over an annual time scale when microclimatic components are included. The increase in demand is less than 1%, however the decrease in radiant heat losses are up to 30%. Using the same methodology with revisions to the building construction and urban geometry, a larger increase in energy demand is expected.

Keywords

Building energy simulation, microclimate, RadTherm, environment, heat island effect, vegetation, EnergyPlus, BES, annual

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Preface

Through the progression of this project, I've come across a number of unforeseen twists and turns that have shaped it in ways I couldn't imagined at the start. Halfway through I was invited by my thesis hosts ThermoAnalytics, to attend their European User Group Meeting and present the building energy simulation model. Having discussions with people outside of the project, and the industry, gave me some alternatives previously overlooked. I did some additional literature searching and found very valuable work I had previously missed. Had I not found that work, the results of this project could have been very different.

The results, however, are still not as I would have hoped. When I first started, I was focused on modeling a super low-energy building, thinking the microclimatic conditions would be more significant when energy consumption is so little. Looking back now, I actually don't see any importance to using the Passive House construction and feel the results would be more interesting and relevant using a building which is more representative of the wider building stock. You always see the past in 20/20.

Looking forward, I hope this study can be used as a springboard into further research. I do believe in the models, but future work should be concentrated focus on the urban environment and geometry which better represents the real world. I can envision a number of additional studies that can be built off of this work, and I hope others can see the same.

I'd like to thank all of the people who have helped make this project happen. I would have had many frustrating days and nights had I not had the support of my host company, ThermoAnalytics. Thank you to my advisor Tony Schwenn for making all of the logistics happen and being my mole while I'm 10,000 kilometers away. To Dr. Al Curran, for supporting the project and giving me access to the resources at ThermoAnalytics. To Stephen Patterson, for answering all of my technical questions, I'd probably still be scripting now without your help. And to Craig Makens, for inviting me to present at the UGM. I also have to thank my advisor at KTH, Jörgen Wallin for keeping a research rookie like me on the right track.

Nelson Sommerfeldt

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Nomenclature

3D-CAD	Three dimensional computer aided design
AOI	Area of interest
ARI	Air Conditioning and Refrigeration Institute
ASHRAE	American Society of Heating, Refrigeration and Air Conditioning Engineers
BES	Building energy simulation
BES/MC	Building energy simulations with microclimate
CAE	Computer aided engineering
CFD	Computational fluid dynamics
Co-simulation	A modeling technique which leverages the strengths of two simulation programs
DOE	United States Department of Energy
EIA	Energy Information Agency
EnergyPlus	Building energy simulation program produced by the U.S. Department of Energy
ENVI-met	Microclimate modeling program produced by Dr. Michael Bruse
Excel	Microsoft Excel 2010
HVAC	Heating, ventilation and air conditioning
IR	Infrared
LEED	Leadership in Energy and Environmental Design
MC	Microclimate
Met Tower	Meteorological station used for collecting weather data
NREL	National Renewable Energy Laboratory
NRMS	Normalized root mean square (difference)
SHGC	Solar heat gain coefficient
SIP	Structurally insulated panels
TAI	ThermoAnalytics, Inc.
TMY2	Typical meteorological year (version 2) weather file
TRNSYS	Building energy simulation program produced by Thermal Energy Systems Specialists
U.S.	United States
USBGC	United States Green Building Council

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Units

°C	Degrees Celsius, SI unit of temperature
ACH	Air changes per hour
cm	Centimeter, SI unit of length
J/kg-K	Jules per kilogram times kelvin, SI units for heat capacity
J/s	Jules per second, equivalent to watts but rewritten for context
K	Degrees kelvin, standard SI unit of temperature
kg/m^3	Kilograms per cubic meter, SI unit of density
kg/s	Kilograms per second, SI unit of mass flow
kW	Kilowatt, SI unit of power
km	Kilometer, SI unit of length
L/min	Liters per minute, SI flow rate units used in RadTherm
L/s	Liters per second, SI unit of flow
m	Meter, standard SI unit of length
m/s	Meter per second, SI unit of velocity
m^2	Square meter, SI unit of area
m^3	Cubic meter, SI unit of volume
mm	Millimeter, SI unit of length
Pa	Pascals, standard SI unit of pressure
W	Watts, standard SI unit of power
W/m^2	Watts per square meter, heat flux or method of specify power density of a zone
W/m^2-K	Watts per square meter – Kelvin, SI units for u-values

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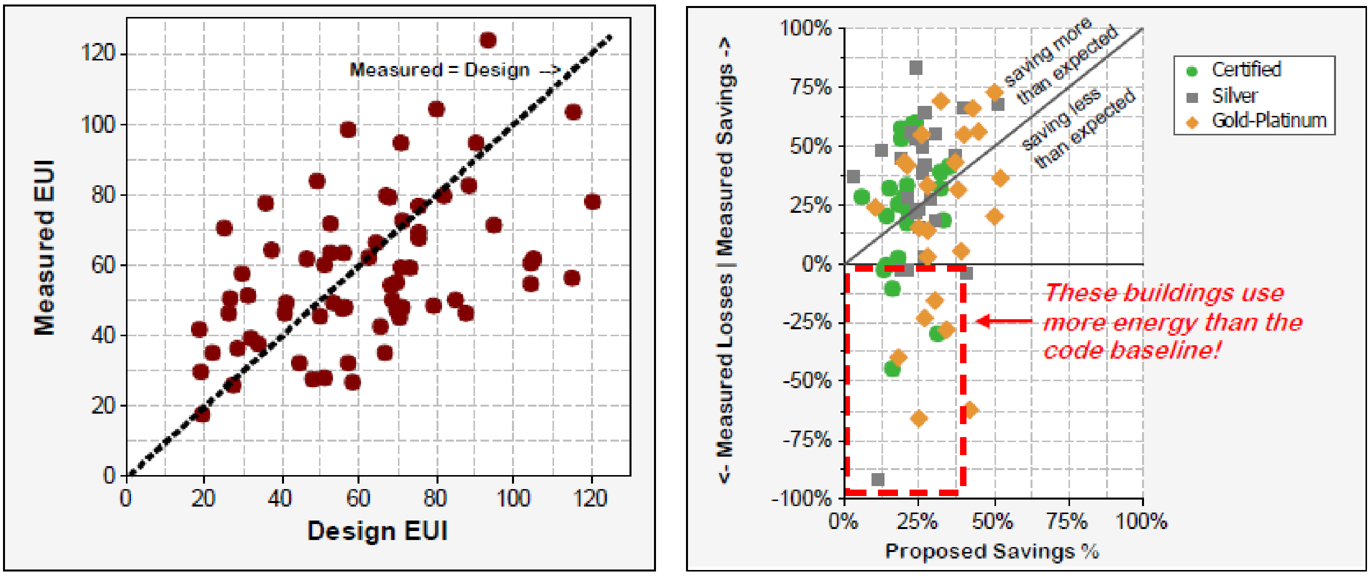
1 Introduction

In light of the recent research on humanity's impact on the environment, atmosphere and natural resources, a movement is growing to reduce energy consumption in the built environment. Buildings account for over 35% of the energy demand in OECD countries, making them a prime target for improvement. (EIA 2011) To help building owners and occupants quantify the value and performance of a "green building," ratings systems have been developed. While there are many systems in existence, the most popular in the United States is LEED administrated by the USGBC. The popularity has grown exponentially since its founding in 2000, and now certifies nearly 12,000 commercial and over 19,000 residential buildings worldwide. (USGBC 2012)

The single largest topic of interest in the LEED system is energy, and a prerequisite for certification is the demonstration of energy efficiency through computer modeling. There is a vast array of building energy simulation models in existence, many with a specialized purpose. (Crawley, Hand, et al. 2008) (Al-Homoud 2001) Models of all types inherently require some level of simplification, ultimately leading to error. However, the incredibly complex nature of buildings and the difficulty of modeling them are leading to excessive error. A 2008 study revealed that LEED certified buildings often have a considerably different energy demand in operation than what was predicted during modeling. (Turner and Frankel 2008) In Figure 1.1, the chart on the left shows that actual usage can vary by up to 30%, and the chart on right shows that while many buildings perform better than expected, many are worse and sometimes even worse than the baseline energy code. The source of these errors is not explicitly known, and while they could be due to a misrepresentation of the use of the building there are physical assumptions left out in many models that could also be to blame.

Figure 1.1 – Modeled vs. actual energy demand in LEED certified buildings (Turner and Frankel 2008)



The most common and popular building simulation tools use standardized weather inputs as a boundary condition surrounding the structure of interest. These weather inputs are typically collected at locations far removed from the built environment, most often at airports. Urban landscapes are known to have a significant effect on local environmental conditions, particularly the heat island effect. BES programs often take simple shading and radiant effects into account, however the target building does not interact with the surrounding environment and thus the microclimate condition cannot be modeled.

(U.S. DOE 2011, p.52) By omitting this microclimatic variable, BES programs are accepting a significant source of error in urban environments. (de la Flor and Dominguez 2004) (Santamouris, et al. 2001)

Several studies have attempted to bring the microclimate variable into building energy simulations with various methodologies. Oxizidis et al. (2008) used a synthetic weather generator to capture urban heat island effects, but it could not handle local convection variables. He et al. (2009) built a complete thermal solver into a commercial Japanese 3D-CAD program, which also did not take local convection into account. Mochida et al. (2006) used a co-simulation technique with CFD and TRNSYS; however it was focused on interior environmental conditions. Yang et al. (2012) created a custom co-simulation technique using EnergyPlus and ENVI-met, but has only presented a methodology without results. Bouyer et al. (2011) use a custom thermal solver co-simulated with Fluent CFD code where they identify the significance of each type of microclimate interaction, concluding that local IR radiant and convective heat fluxes are significant and cannot be ignored when doing building energy simulations.

Aside from the methodological limitations mentioned above, there are two practical limitations to all of these studies; limited access and computation time. Accessibility to these methods is restricted in that some portion of the solver has been custom built by a research team. Many models do start out in a research environment; however there are commercial options available which would make mass adoption potentially faster and easier. In addition to speed to market, the speed of the simulation is very important in a commercial setting. The use of a mesh-based numerical solver is in many ways advantageous and possibly necessary for doing a transient BES/MC study. However, the incredibly lengthy simulation times can be limiting for commercial use. In one case involving co-simulation with CFD, the simulation time was the same as the time of interest, one week, and that was only using a stead state wind velocity. (Bouyer, Inard and Musy 2011) If BES/MC modeling is to become effective in industry, the simulation times must be reduced.

One commercial option to handle microclimate simulations is RadTherm from ThermoAnalytics. (ThermoAnalytics 2010) RadTherm is traditionally used in defense and automotive sectors, but has been identified as a relevant tool for building physics studies because of its radiant exchange model. (Kapur 2004) It is a mesh-based, numerical thermal solver with a particular strength for handling radiant interactions with vegetation. RadTherm has been examined before for use in building energy simulations with noted advantages over current art, however being a more fundamental thermal solver it is limited by a lack of building sector specific features. (Sami and Gassman 2006) (Lahti and Lindberg 2006) This limitation can be overcome because, much like TRNSYS, it has a scripting shell that allows engineers to custom build functions that can interface with the core solver.

Being a more general thermal solver, rather than building specific, gives RadTherm the power to model a much more divers set of situations. Innovative architects are now incorporating shading, louvers, and vegetation into facades, as well as manipulating the local environment to utilize as many passive energy saving techniques as possible. Urban planners are also starting to explore techniques for adding vegetation or water mass and the effect this has on the heat island effect in urban areas. Research engineers are searching for new construction techniques to reduce or eliminate thermal bridges. The construction industry has often relied on “rules of thumb”, and a new era of building design and engineering is constantly pushing the limits of what computer models can do. With its high degree of flexibility, RadTherm is capable of all these studies as well as advanced human comfort modeling. For these reasons, RadTherm is an interesting commercial software package for the building industry and integrating building energy simulations with microclimatic effects.

2 Objectives and Scope

There are two primary objectives of this study; first is to establish the legitimacy of RadTherm as a building energy simulation tool. There have been building simulations done with RadTherm, however nothing on an annual time scale and to author's knowledge none with an integrated HVAC system model. Therefore a model must first be established, then a methodology for performing annual simulations. As has been already noted, mesh-based numeric solvers can require extremely long computation times. Therefore the annual simulation methodology must minimize simulation time while maintaining accuracy standards.

The second primary objective is to demonstrate the importance of microclimate modeling in annual building energy simulations. Microclimate models have been done before as noted above, however all prior examples are done with time scales less than one year. Most of the common building rating systems require annual simulation lengths, and thus this time scale is most relevant for determining the absolute performance of a building or urban planning scheme.

A secondary objective is to demonstrate these modeling techniques as useful procedures for industry. All of the research and knowledge in the world lacks value if it cannot be practically applied. Field measurements and previous work have determined that the effect microclimates have on buildings is significant. The challenge is to carry this phenomenon into common modeling practice.

To carry out this study, there is a considerable amount of model development necessary. While every effort will be made to ensure absolute consistency when determining RadTherm's building modeling performance, any discrepancies caused by the core thermal solvers will not be resolved or discussed at length. RadTherm has been independently validated in a wide array of situations and is believed to be an accurate program for modeling heat transfer. Additionally, there may be situations when details pertinent to geometry construction may be reasonably approximated in the interest of time. The physical behavior of the built environment is under continuous study, and it is not this work's purpose to resolve in detail several areas of research.

3 Methodology

This study is constructed as a combination of three smaller studies, which work together in succession to achieve the objectives. Prior to performing any studies, a model must be constructed in RadTherm. A number of simulation tools which are native to most building modeling tools are not in RadTherm, and therefore must be custom built. Once a complete model has been created, a process of how to use it must be determined. This comes in the form of a mesh resolution test and the actual annual simulation methodology. These three steps are pre-requisites for establishing a comparative model in RadTherm, which can then be used in the microclimate study. Baseline criteria are also necessary to ensure the RadTherm model is relevant. This chapter is an overview of the study process, with additional details located in each specific topics chapter.

3.1 Equipment

Given that the nature of this study is to compare software models, the only necessary equipment are computer hardware and the simulation software. The description of hardware is relevant due to the use of simulation run times as a performance metric.

3.1.1 Hardware

The computer used in all simulations is an Apple MacBook Pro running Windows 7 Professional natively through Bootcamp. The processor is a 2.53 GHz Intel i5 Quad Core and there is a total allotment of 8 GB of DDR3 RAM.

3.1.2 Software

The target software for performing the BES/MC study is RadTherm, which has already been discussed in the Introduction above. The comparative building energy model is EnergyPlus, created by the U.S. Department of Energy. It is one of the most comprehensive, widely used, tested and respected building modeling programs available today. A listing of published research and testing performed with EnergyPlus can be found on the DOE website. (U.S. DOE 2012) Managing the model's complexity and text based interface has led to the creation of commercial graphical interfaces. One such interface, DesignBuilder, will be used as a pre-processor for creating and editing models for use in EnergyPlus. In addition to providing a GUI, DesignBuilder contains a vast number of materials and templates for use in EnergyPlus, as well as some of its own modeling features. It should be noted that the two programs have specific roles, thus their names are not interchangeable and are not treated as such in this paper. Details on how the comparisons will be made are in the Performance Parameters section below.

The final program used in the study is Microsoft Excel 2010. Several custom macros are used to create inputs into RadTherm, which are done through an ASCII file interface. Descriptions of use for these macros are listed below in the BES Model Construction chapter.

3.2 Model Construction

A proper analysis of RadTherm requires a complete building energy model and a suitable control model. Materials, internal gains, HVAC and weather inputs are done in RadTherm such that they are equivalent to EnergyPlus. Building geometry is arbitrarily based on the Passive House Standard and created independently in each program with no discrepancies between them. RadTherm is a much more universal program, and thus does not have as many building specific features as DesignBuilder. Therefore, HVAC control and internal gains models are built through the use of RadTherm curves and scripts, which can be integrated with the thermal solver. The design of the models is described in further detail in the BES Model Construction chapter below.

3.3 Mesh Resolution Test

RadTherm uses a mesh to represent the building geometry and carry out thermal solutions. The resolution of the mesh has a twofold effect on a simulation; run time and accuracy. The ideal mesh size will be such that run time is minimized without causing an unacceptable degradation in accuracy. Since mesh resolution will be a critical setting in all simulations throughout the study, determining an appropriate meshing strategy must be done first.

Buildings are very large subjects with a high level of exterior and interior details. The level of detail required in a mesh can be potentially driven by an individual building’s features. For example, if a building has a window size that is 1 m by 0.5 m in size, a 1 m square facet will not be able to accurately represent the window. Mesh facets are certainly capable of being non-square in shape, with an aspect ratio limitation of roughly 4-to-1 for stable solving. (ThermAnalytics 2011) For purpose of simplicity, this study maintains a square aspect ratio for facets as well as an examination of the effect of creating windows and doors with only one facet. All of the mesh facet sizes to be tested are listed below, and all sizes will be tested with the single facet windows and doors.

- 10, 25, and 50 cm per side

The mesh resolution study is performed first, and in the interest of time the time scale will not be annual. Simulations will be performed during the winter design week and the summer design week, the coldest and hottest weeks of the year, respectively. These weeks are selected to test the maximum and minimum conditions of the model, and acceptable results for both simulations are considered a qualification for annual simulations. Further methodological details are described in the Mesh Resolution Test chapter below.

3.4 Annual Simulation Methodology

Running transient simulations can often be a time consuming processes, even on a short time scale. When dealing with an annual time scale and over 35,000 time steps, any opportunity to save time is valuable. In the case of EnergyPlus, speed is achieved by using a single thermal node for each building element (i.e. wall or window in a single plane). RadTherm uses a meshed based solver, which is much more powerful since it adds two more dimensions to the building element, but requires many more nodes and thus more calculation time.

This part of the study will use the meshed geometry created in the Mesh Resolution Test to test three annual simulation methodologies, with the objective to minimize the time required to get results. The first method is simply running RadTherm like EnergyPlus, where every time step in the year is run. The other two methods use a custom built weather file which takes the averages of each hour in the day for a given time scale to create an average day simulation. The time scales to be averaged are one week and one month. The three methodologies are listed below;

- Run an entire year
- One average day per week, 52 simulations for the year
- One average day per month, 12 simulations for the year

The results from the abbreviated techniques are then combined post process to build up a full 8760 hour annual run. In each case, the time steps and result write frequency will remain constant at 0.25 and one hour respectively, and only the length of the simulation will change. 0.25 hour time steps are regarded as acceptable for thermal solutions by the developers of EnergyPlus, but it is recommended that when using the HVAC solver a 0.16667 hour (10 minute) time step should be used. (DesignBuilder 2012) Given the extremely simple nature of the building and HVAC model, the longer time step is acceptable and has been confirmed by testing each time step in EnergyPlus with no deviation in results.

3.5 Microclimate Modeling

This study will demonstrate the significance of modeling microclimates by comparing the effects of adding surrounding environmental features in each BES program. RadTherm accepts weather inputs and applies them much in the same way EnergyPlus does. The key feature in RadTherm is that it calculates temperatures and radiant exchanges with any surface nodes in the model; whereas EnergyPlus has a default emissivity for exterior objects and sets their temperatures with the ambient air. The RadTherm model will take into account the actual radiant effect the surrounding environment has on the target building.

The second microclimatic component is local air temperature. Neither program by default can modify the ambient weather file; however RadTherm has features which can simulate local weather with customized air nodes. Four air nodes are used; one which represents the air directly above the terrain and around the buildings, another to represent the air above the ground layer up to three times the height of the buildings, and pre-treating nodes for each. The ambient air surrounding the AOI will be introduced to the air nodes through advection links driven by the weather file wind speed. Prior to entering the AOI, the ambient air will be pre-treated as if it has passed through 5 km of terrain similar to the AOI.

Within each program, three scenes are built. The first scene is rural where no additional buildings are added, only trees and the terrain is entirely covered in grass. Scene two is suburban, with a looser building grid, a mixture of asphalt and grass on the terrain, and trees added. Scene three is urban, with buildings placed in a dense grid around the target building and the terrain between them asphalt. Each scene is 110m by 110m and sits on a flat terrain. The same target building used in model development is placed at the center of the scene and remains constant throughout the study.

EnergyPlus only has a single model for each scene, whereas features in RadTherm are added in stages in order to identify which component of the microclimate has the greatest effect. The first stage is to update the default background and add the surrounding buildings and trees. This stage will be the most similar to the EnergyPlus model, which is not capable of modeling a dynamic terrain. The second stage is to add a faceted terrain, which models dynamic radiant exchange and more realistic ground modeling. The third is to add the air nodes to create a local air temperature within the scene. Model, scene and calculation details are described in full in the Microclimate Model Description chapter below.

3.6 Performance Parameters

To validate the RadTherm model, a reputable reference case is necessary. Ideally the reference would be based on empirical data, however those resources are unavailable. In the foreword of ASHRAE Standard 140 (2011), the authors state that the results of a collection of models which have been subject to “analytical verification, empirical validation, and comparative testing studies” is an appropriate benchmark to determine the appropriateness of a new model, and that none of the models can be deemed absolutely correct.

In the same vein, many situations rely on the subjective judgment and interests of the modeler to drive the acceptance of results. This study aims to be as objective as possible while taking into account the statements made by ASHRAE. EnergyPlus will be a benchmark model, and tolerance criteria will be applied to the results created by it and RadTherm to determine the appropriateness of the RadTherm model. These parameters will only be used to qualify the RadTherm model during the Mesh Resolution Test and Annual Simulation Methodology development. The microclimate modeling is expected to show significantly varied results since it cannot be recreated in EnergyPlus, but the same statistical measurements will be done for reference.

There are three parameters of interest that will be used to determine the acceptability of the RadTherm results; total energy difference, the correlation coefficient, and the NRMS. The total energy difference is simply the percentage difference between the summations of predicted energy demand from RadTherm to EnergyPlus. This is represented by Equation [1] below. For a RadTherm simulation to be considered valid, the total energy difference must be within 10%.

$$\Delta E = 1 - \frac{\sum E_{rt}}{\sum E_{ep}} \times 100\% \qquad \text{Equation [1]}$$

E_{ep} = total energy demand for a given time frame by EnergyPlus (kWh)

E_{rt} = total energy demand for a given time frame by RadTherm (kWh)

The correlation coefficient is used as a measurement of how well the pattern of two data sets matches each other. This measurement is useful in that it can report in a single number the differences in each model's response to specific events, i.e. internal gains, solar radiation or ambient temperature changes. The correlation coefficient is calculated using Equation [2], has a range from 0 to 1, and must be higher than 0.9 to be acceptable.

$$C(X,Y) = \frac{\sum(x-\bar{x})(y-\bar{y})}{\sqrt{\sum(x-\bar{x})^2 \sum(y-\bar{y})^2}} \qquad \text{Equation [2]}$$

x = data point in a RadTherm set

$\bar{x}$ = mean of a RadTherm set

y = data point in an EnergyPlus set

$\bar{y}$ = mean of an EnergyPlus set

Two data sets which are perfectly correlated can still have completely different values, and therefore a parameter is necessary to determine what level of deviation is present. The RMS, or root mean square, is a measurement of average deviation between two data sets given in the units of the data sets. Normalizing the RMS is to divide it by the total range of values in the target data set, resulting in a percentage, which puts the absolute RMS value in perspective. The NRMS value is determined with Equation [3] below, and also has an acceptability limit of 10%.

$$NRMS(X,Y) = \frac{\frac{\sqrt{\sum(x-y)^2}}{n}}{x_{max} - x_{min}} \times 100\% \qquad \text{Equation [3]}$$

x = data point in a RadTherm set

y = data point in an EnergyPlus set

n = count of data points (equal in both sets)

x_{max} = maximum data point value in the RadTherm data set

x_{min} = minimum data point value in the RadTherm data set

4 BES Model Construction

This chapter describes the physical building model being used. In several instances, the creation of the model in RadTherm versus DesignBuilder is very different. However, it is a priority to ensure that there is a minimal difference between the models during the benchmarking/calibration portion of the study. In the following sections is a detailed description of the model and any differences that occur in the RadTherm model.

It is also worth noting that while an effort has been made to create a reasonably realistic condition, creating a model which perfectly represents a real world scenario is not the intention. More important is that the model inputs match exactly. This issue comes up several times during model creation since RadTherm does not have all of the complex building specific algorithms included in EnergyPlus. An attempt has been made to avoid gross approximations, and any simple approximations are noted. The potential for additional algorithms in RadTherm is discussed in Appendix A.

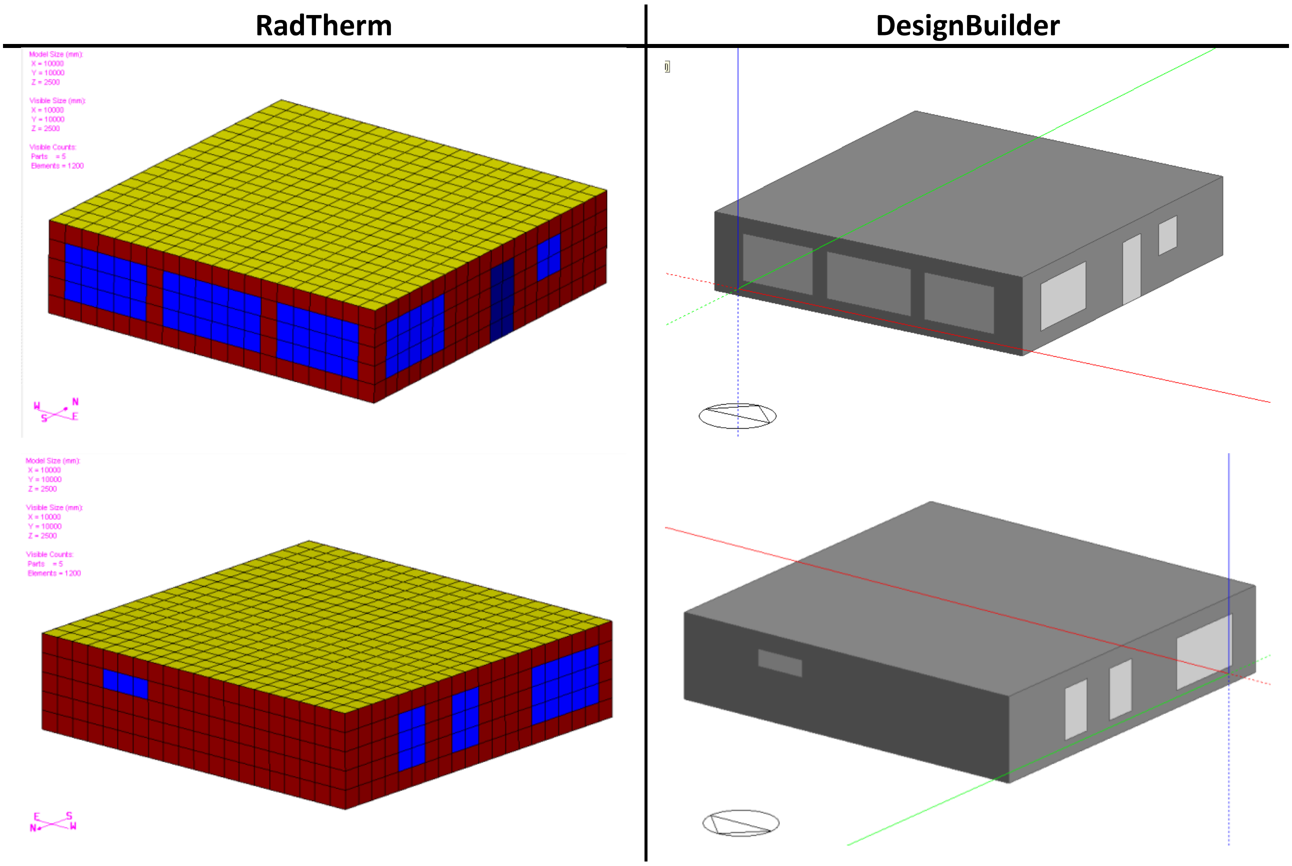
4.1 Building Description

The building being used for the first three studies is intended to be a simple, one room structure for ease of calculation, geometry creation and fast simulation times. The building is 10m by 10m with a 2.5m high ceiling. The intent of the building construction is to follow the Passive House Institute's guidelines. (Passive House Institute 2011) A passive house focuses on very airtight construction, super insulated envelope, and a heat recovered mechanical ventilation system. Specific guidelines include;

- infiltration rates below 0.6 ACH at 50 Pa,
- a building envelope with average U-value lower than 0.15 W/m^2-K,
- windows should have U-values under 0.8 W/m^2-K and SHGC of at least 50%, and
- a heat recovery rate of at least 80%.

In Figure 4.1 below, screen shots of the building are shown from each program. The RadTherm window has a compass showing primary directions in the lower left hand corner. DesignBuilder has an arrow indicating north, also in the lower left hand corner. The area weighted average U-value of the entire envelope works out to be 0.254 W/m^2-K, not meeting the standard. This is primarily due to the windows, which are discussed in detail below.

Figure 4.1 – Images of the building model in RadTherm and DesignBuilder



RadTherm **DesignBuilder**

4.1.1 Materials

Both RadTherm and DesignBuilder are equipped with material libraries, with an option to add custom materials as needed. The RadTherm library is somewhat more generic, while the DesignBuilder materials are specifically geared towards the construction industry and include a very large and diverse selection with references to the source of the data. The detailed accuracy of the material measurements is irrelevant for this study so long as they are the same in each model. Material properties are pulled from DesignBuilder and new materials are made to match in RadTherm. The properties of all materials used are listed in Table 4.1 below. The emissivity values in DesignBuilder seem to be set to a generic 0.9 value, whereas in RadTherm these materials have varying values. Since a significant difference with RadTherm is the ability to model radiation interactions, this emissivity will be more significant in the Microclimate study and values will be adjusted then.

Table 4.1 – Building Material Properties

Material	Conductivity	Specific Heat	Density	Emissivity	Absorptivity	Source
Oak Siding	0.160	1260	720	0.9	0.6	CIBSE
Plywood	0.150	2500	560	0.9	n/a	CIBSE
Expanded Polystyrene	0.040	1400	15	0.9	n/a	URALITA
Gypsum	0.250	1000	900	0.9	0.5	ISO 10456
Asphalt	0.700	1000	2100	0.9	0.85	ISO 10456
Cast Concrete	0.800	840	1300	0.9	n/a	-
Foam Rubber	0.060	1500	90	0.9	n/a	ISO 10456
Pine Flooring	0.012	1380	510	0.9	0.6	CIBSE
Polyurethane	0.028	1470	30	0.9	n/a	CIBSE
Window Glass	0.900	754	2530	0.9	0.837 (trans.)	-

4.1.2 Wall Construction

While not a critical feature of this study, a key technique to reducing heat transfer through the building envelope is to reduce or eliminate thermal bridges. In this vein, the walls are being constructed using SIP panels, which are a sandwich of plywood filled with extruded polystyrene. SIP construction is actually much easier to model in RadTherm, and in EnergyPlus thermal bridges (i.e. stud walls) cannot be accounted for at all. Wall construction is described in Table 4.2 below. Average U-value for the walls is calculated by DesignBuilder at 0.095 W/m^2-K.

Table 4.2 – Wall construction

Layer	Material	Thickness
Outermost (1)	Oak Siding	13 mm
2	Plywood	13 mm
3	Expanded Polystyrene	400 mm
4	Plywood	13 mm
Innermost (5)	Gypsum	13 mm

4.1.3 Windows

Another feature of low energy buildings is to maximize the use of passive solar energy. In following this technique, a majority of windows have been placed on the south side of the building, as seen in Figure 4.1 above. The location of the windows is not critical in testing the two programs so long as the window orientations are the same. This layout does however add emphasis on the handling of solar radiation. EnergyPlus has several algorithms for the distribution of solar radiation within a zone, and the most complex and realistic one has been selected for this study since it is the only option in RadTherm.

As mentioned above, the Passive House Institute recommends an average U-value of 0.8 W/m^2-K for the windows. This is typically achieved by using three panes of glass with a noble gas in between, usually argon or krypton. RadTherm allows the construction of multi-layers parts with transparent materials; however the only gas that is permitted to be used between the layers is standard air. This limitation prevents the windows from being able to reach the U-value standard, but again they are the same between models which is most important. U-values calculated by DesignBuilder are 1.817 W/m^2-K and the SHGC is 0.579. Additionally, because the building site is in a cold climate, a low-emissivity coating (ε=0.1) has been placed on surface 5. Specific construction details are listed in Table 4.3 below.

Table 4.3 – Window construction

Layer	Material	Thickness
Outermost (1)	Window Glass	3 mm
2	Air Gap	6 mm
3	Window Glass	3 mm
4	Air Gap	6 mm
Surface 5	Low-E Coating	ε=0.1
Innermost (5)	Window Glass	3 mm

4.1.4 Door

Door construction is of a simple, insulated exterior door without a window. Materials and thickness are chosen based on creating a door with minimal heat transfer while still conforming to typical door construction standards. Details are listed in Table 4.4 below and the U-value is calculated by DesignBuilder at 0.567 W/m^2-K.

Table 4.4 – Door construction

Layer	Material	Thickness
Outermost (1)	Oak Wood	6 mm
2	Polyurethane Foam	40 mm
Innermost (3)	Oak Wood	6 mm

4.1.5 Roof

Construction of the roof follows the same principles as the walls; maximum insulation and minimum thermal bridges. The only difference between them is the outermost layer material and the thickness of the insulation. Details of construction are shown in Table 4.5 below. DesignBuilder limits layer thicknesses to 500 mm, which given the insulation material is enough to get an acceptable U-value of 0.078 W/m^2-K.

Table 4.5 – Roof construction

Layer	Material	Thickness
Outermost (1)	Asphalt	6 mm
2	Plywood	13 mm
3	Expanded Polystyrene	500 mm
4	Plywood	13 mm
Innermost (5)	Gypsum	13 mm

4.1.6 Ground Floor

Ground floor construction is intended to mimic how a new passive house would be built. The somewhat unconventional feature is insulation underneath the concrete slab, however in super low energy construction this has become commonplace. Detailed construction is shown in Table 4.6 and the resulting U-value is 0.170 W/m2-K.

Table 4.6 – Ground floor construction

Layer	Material	Thickness
Outermost (1)	Expanded Polystyrene	200 mm
2	Cast Concrete	100 mm
3	Foam Rubber	6 mm
Inner most (4)	Pine Flooring	6 mm

4.1.7 Infiltration

Calculating infiltration is very complex and subject to a number of uncertainties. The factors at play include; building envelope tightness, height of the zone, ambient air temperature, wind speed, wind shear, wind direction and the surrounding environment. (U.S. DOE 2011, p.96) EnergyPlus gives the option to use a complex algorithm to determine infiltration, use a constant rate, or to even turn the option off. Any similarly complex algorithm can be programed into RadTherm and applied to an advection link, but in the interest of time and simplicity this value will be left as a constant rate. The constant infiltration rate is 0.038 ACH (159 L/min), and is based on the maximum Passive House value (at 50 Pa) and the average wind speed, calculated using the methodology described by the Pacific Northwest National Laboratory. (Gowri, Winiarski and Jarnagin 2009)

Like many other settings, the importance here is to ensure the two models behave similarly, not necessarily to mimic a real world situation. DesignBuilder documentation even recommends not using the complex infiltration algorithms for most models due to the additional computation time required, so using a constant value is not uncommon.

4.2 Weather

The building site has been arbitrarily chosen as Stockholm, Sweden. The weather surrounding a building is one of the primary driving factors in its design, so naturally the weather data selected for simulations must be selected carefully. There has been over 30 years of research and development work done on creating a weather file that can represent a typical year. In 1998, ASHRAE published an article in their transactions that describes the effects various weather data can have on simulation results. (Crawley 1998) Their conclusion is that TMY2 (Typical Meteorological Year) or WYEC2 (Weather Year for Energy Calculations) data collections are the most representative of expected long term weather. EnergyPlus uses the TMY2 data set in their default *.epw weather file. The same weather data will be used in RadTherm. The weather data for Stockholm is taken from one of two airports; Bromma or Arlanda. While the Bromma airport is much closer to the city center, TMY2 data is only available for Arlanda (Latitude: 59.65°, Longitude: 17.95°, GMT+1).

4.2.1 TMY2 for RadTherm

ThermoAnalytics has a relatively convenient method for acquiring local weather data. The website WeatherUnderground provides historical measurements in CSV format for weather stations all over the globe. Using a third party program called Perl, a custom TAI script converts the WeatherUnderground CSV file into its own weather data file. This technique can work well for simulations of specific weather events or conditions, which is what RadTherm is commonly used for. However, no single year can represent long term weather patterns. (Crawley 1998)

The TMY2 data set uses the actual, hourly weather measurements for an entire month, but then combine months from various years. The goal is to provide real fluctuations on an hourly basis, but have months that are most representative of a long term average. It contains all of the weather data critical to creating a RadTherm simulation (temperature, humidity, pressure, wind, clouding, etc.), as well as measured solar and luminance data. The DOE has created *.epw weather files for over 2100 locations around the globe, over 1000 of those in the U.S. (U.S. DOE 2011) The *.epw format is also a common option when using artificial weather data created for very specific locations, such as Meteonorm. For this study, the Perl script provided by TAI for use with WeatherUndergound files is modified to handle a custom built TMY2 data set.

4.2.2 Measured Solar Data

RadTherm includes a solar model that is capable of providing radiation values so long as cloud cover and rain fall data are in the weather file. EnergyPlus uses measured solar data from the TMY2 file, so it would be appropriate to use the same data set in RadTherm as well. RadTherm accepts diffuse and direct horizontal solar measurements as well as direct normal. The TMY2 data set includes all of these plus extra-terrestrial values.

4.2.3 Ground Temperatures

Techniques for modeling ground temperatures is still widely discussed and actively researched today. What is certain is that measured ground temperatures are not appropriate for use under the building since they are for undisturbed sites, and the ground under a building is certainly affected by the building. For large buildings, EnergyPlus engineers recommend using a temperature that is 2°C below the interior temperature of the zone at ground level. (DesignBuilder 2012) However, at 100m^2 it is hard to call the test model a large building. At time of writing, no documentation has been found describing a technique to use for smaller buildings; however it is suspected to be closer to the measured ground temperatures than the technique recommended for large buildings.

Some preliminary testing has shown that ground temperatures do make a significant difference in how much heat is lost through the ground floor. Using DesignBuilder, an annual simulation was run using a constant 14°C ground temperature (the default) and the 4.0m deep undisturbed ground temperature (the most conservative of the three measured depths) supplied in one of the EnergyPlus complementary weather files. The results showed that in colder months, over twice as much heat can be lost through the floor. In an attempt to find a compromise and move the study forward, an arbitrary method for determine ground temperatures is used. An average is taken of the expected indoor zone temperature and the 0.5m deep measured ground temp. The accuracy of this method to actual ground temperatures is certainly debatable, but the critical feature of this study is that the same values are used in each model. The 0.5m measured ground temperatures, indoor temps used and resultant ground temps are listed in Table 4.7 below.

Table 4.7 – Calculated ground temperatures

Month	0.5 m Depth (m)	Zone Temp (°C)	Calc. Temp (°C)
Jan	-2	21	9.5
Feb	-2.8	21	9.1
Mar	-1.4	22	10.3
Apr	0.9	23	11.95
Mar	7.0	24	15.5
Jun	11.6	25	18.3
Jul	14.8	25	19.9
Aug	15.7	25	20.35
Sep	14.1	24	19.35
Oct	10.5	23	16.75
Nov	5.7	21	13.35
Dec	1.2	21	11.1

4.2.4 Background Conditions

In addition to surrounding temperatures, the surrounding surface conditions are set as the default surface in RadTherm, with an emissivity of 0.9 and an absorption value of 0.7. EnergyPlus has a default emissivity for all surrounding surfaces of 0.9 that cannot be altered in DesignBuilder, but the solar reflection value (1-absorptivity) can be modified and is set to match the 0.7 absorption value. EnergyPlus also has the ability to read in snow depth and adjust the reflectivity based on the presence of snow, while RadTherm would require separate simulations for the seasons. For the winter design week, the surface conditions will be set to snow (emissivity=0.9, absorptivity=0.1), but for simplicity and speed both programs are set to a snowless condition for the annual simulations.

4.3 Internal Gains

Internal gains are heat expelled naturally by people and equipment in a building and play a significant role in the energy balance of a building. In cold seasons they help offset heat generated by the HVAC systems and in summer they are often an unwanted burden on the cooling system. Gains can be from a wide variety of sources at varying intensities depending on the type of building and its use. In this study the building will be assumed to be residential and the gains will be based on typical household activities. This will include heat from occupants, lighting, electronics and kitchen appliances.

Heat can be imposed in three ways; latent, convective and radiant. At the time of writing, RadTherm does not model moisture content in its fluid nodes[1]; therefore latent heat added to the air from occupants is not handled directly by either program. Instead, all heat is considered to be sensible. The sensible heat is imposed directly on the air node and the process of handling radiant gains is described in the Radiant Gains Methodology section below. In each heat source listed, the radiant fraction is listed and is the value that determines the division between the two types of heat transfer.

---

[1] According to TAI, moisture transfer to air nodes is in development for 2012 release.

4.3.1 Occupants

The total heat gain from people is dependent on three factors; how many people are in the space, what kinds of people they are and what they are doing. For this study, it is expected that five men will be occupying the building. The count is arbitrary and men were chosen because inputs are simpler. Women and children, due to their smaller size are expected to expel less heat. This is handled by an adjustment factor that reduces the metabolic power rating. To simplify the process, a factor of one is chosen indicating all men. The activity level, or metabolic rate, has been selected as “standing relaxed” in DesignBuilder, which correlates to a total power output of 126W per person and is a reasonable average for most common household activities.

4.3.2 Lighting

Between mounting fixtures and lamp types, there are a seemingly infinite number of lighting options available. For the sake of simplicity, all fixtures are assumed to be recessed (i.e. can) lighting using compact florescent lamps. Home lighting is assumed to provide 300 lux at working surfaces and the estimated power density for this study is 5 W/m^2-100lux. The lighting is assumed to have a long wave radiant fraction of 0.35, convective fraction of 0.45, and a visible light (short wave radiation) efficiency of 0.20. All energy given off by a lamp will eventually turn into heat; however the form will have an effect on the timing of the gains. Given the very long simulation time steps relative to the speed of light reflecting off of the interior surfaces, the long and short wave radiation are assumed to be same, resulting in a final radiant fraction of 0.55.

4.3.3 Electronics

For this study, electronics consist of home equipment such as televisions, computers, stereos, etc. Like lighting, all of the energy used in these devices will become heat in the room and have a long-wave radiant and convective component. The total power rating of the electronics is 10 W/m^2, or 1000W total, and the radiant fraction is assumed to be 0.20.

4.3.4 Appliances

There is a wide array of electronic gadgets in use in kitchens today; however the primary energy users are the cooktop, oven and refrigerator. While refrigerators have a fairly typical design from one model to another, cooktops and ovens can vary greatly due to fuel sources. For this study, the cooktop and oven are assumed to be electric and assume the same radiant fraction as the electronics, 0.20. The refrigerator is assumed to lack a cooling fan and thus has the same radiant fraction as the other appliances.

Another factor that plays into the gains from kitchen activities is the ventilation hood. EnergyPlus can assume that some fraction of heat is lost through the direct ventilation of the heated air. This value is simply subtracted from the total power value of the gains scheduled for the time step. This setting is available as a way to make inputs easier to handle, but to avoid confusion it is left at zero. The final power rating of the kitchen equipment is 30 W/m^2 or a zone total of 3000W.

4.3.5 Schedules

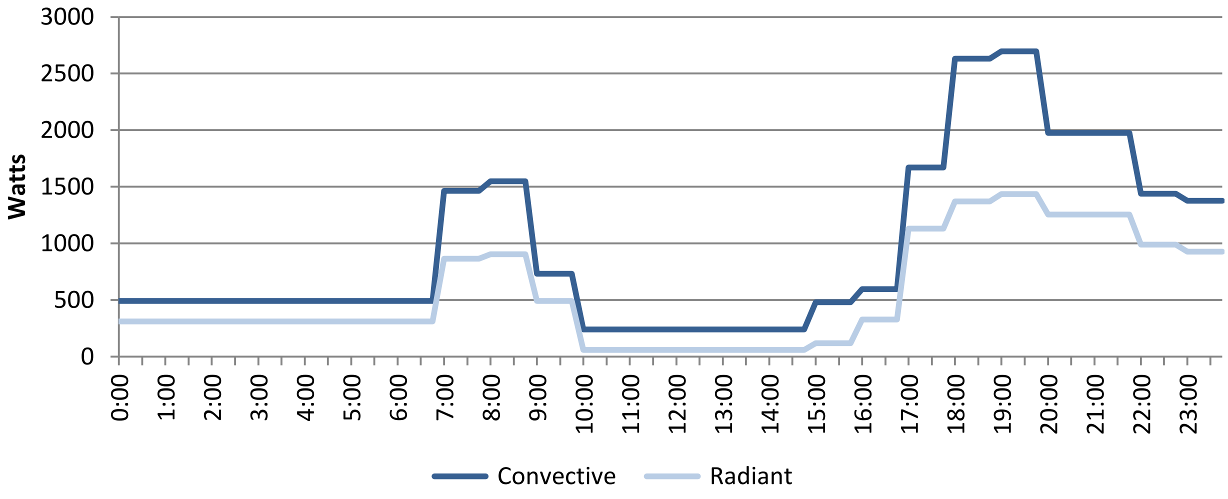
People and equipment are not emitting their full power rating inside a building at all times, and therefore a schedule is necessary to control heat output. Schedules are an independent object in DesignBuilder that can be created using the quick and simple or more advanced and detailed method. In either case, it is possible to create a schedule that varies with day of the week, seasons and holidays. There is a wide array of schedules available as templates, or custom schedules can be created. These schedules can be associated with a given routine, be it occupancy, internal gains or HVAC availability.

RadTherm does not have the same type of scheduling feature, but does have the ability to control variables through curves. Curves can be applied to a wide range of objects within the program, including heat gains. To easily create curves, a macro-enabled Excel file has been created which has all of the power ratings and standard weekday, weekend and holiday schedules set similar to the method used by DesignBuilder. The output is a two column curve, including the hours from the start of the simulation and the power rating or flow rate to be applied. Annual curves with 0.25hr time steps have been created for the convective gains, radiant gains and ventilation (discussed further in the Ventilation section below). The curves are exported from Excel as a CSV, commas are removed in TextPad and the resulting ASCII file imported into RadTherm. The resulting system performs just as the schedule generators in DesignBuilder do and is checked with each simulation to ensure both programs match.

4.3.6 Radiant Gains Methodology

As mentioned above, internal gains are divided into convective and radiant components (latent gains are ignored in this study). Convective gains are imposed directly to the interior air, whereas radiant gains are applied evenly to all interior surface; the default methodology used in EnergyPlus. This distinction is important in that radiant gains will be somewhat delayed in effecting the interior air temperature since they must be absorbed by the surfaces then transferred to the air through convection. Although the even distribution is not completely accurate, it would be nearly impossible to capture the actual emission within a space without knowing every detail of the interior layout. The resultant curves for convective and radiant gains during a weekday are shown in Figure 4.2 below. Weekend curves are very similar.

Figure 4.2 – Internal gains curves for convection and radiation during a weekday



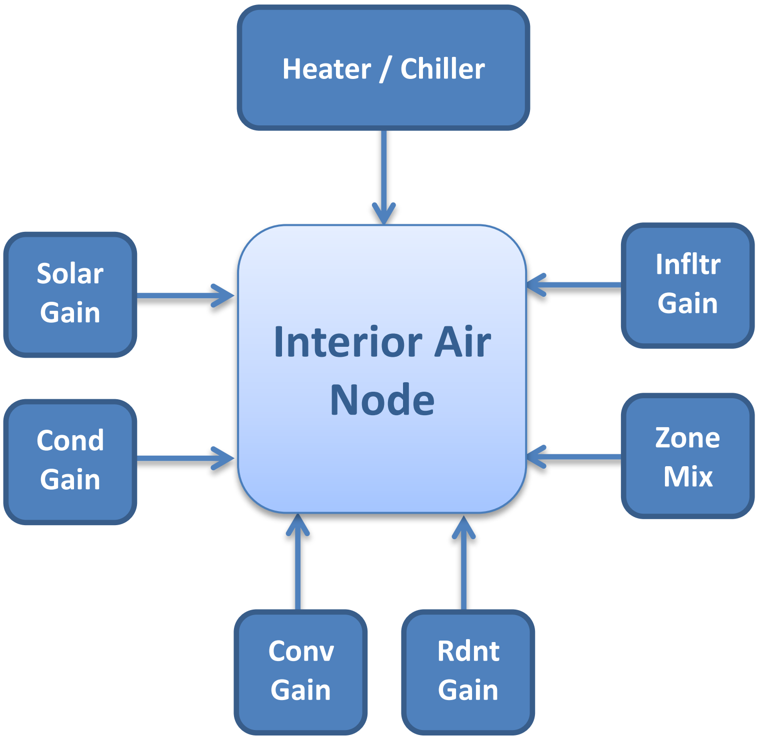
4.4 HVAC Model

There are a few foundational designs for HVAC systems surrounded by numerous options that create an endless supply of variations and make each building a custom installation. A considerable amount of effort has been put into creating a diverse, flexible and accurate modeling engine for HVAC systems in EnergyPlus so it can be used as a universally applicable tool. RadTherm is fully capable of representing an HVAC system, but has no specifically dedicated controls, algorithms or structure to do so. Therefore, an HVAC system must be programmed from scratch and integrated with the thermal solver. Because EnergyPlus is a U.S. government initiative, all of the engineering documentation driving the model is freely available and the HVAC model programmed into RadTherm is largely based on this documentation. (U.S. DOE 2011)

The HVAC and interior node network is built on RadTherm's fluid node parts, advection links and custom scripts which can be assigned to parts or events and run during the thermal solution. Scripting gives the user considerably more power and flexibility in creating tools within RadTherm over DesignBuilder; however it does require a much higher degree of skill. In the interest of time, the HVAC system used for this study is kept very simple. Originally the system was intended to represent the type of system used in a passive house installation, with the key components of; mechanical ventilation, heat recovery and a heating/cooling source. However the heat recovery model had to be abandoned, which is described in the Heat Recovery section below.

HVAC load calculations start with a heat balance on the zone, a visual representation of which is shown in Figure 4.3. The left side boxes represent interactions through the envelope, which are solar radiation through the windows and conduction through all surfaces. The bottom boxes represent the internal gains described in the previous section. The right side boxes represent air mass flow not controlled by the ventilation system. The top box is the HVAC system and is described in the following sections.

Figure 4.3 – Diagram of zone heat balance with all thermal and mass flows

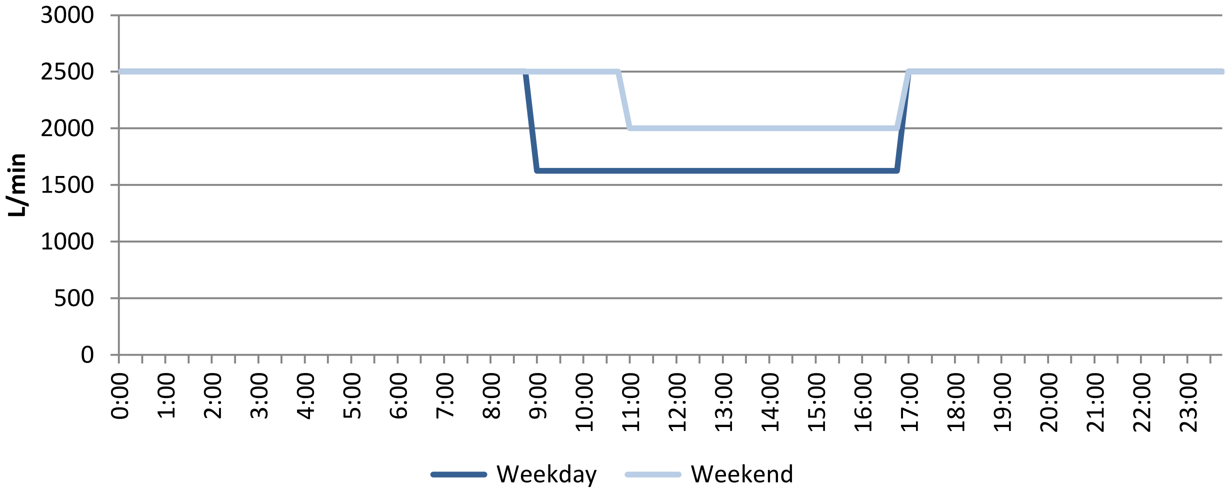


4.4.1 Ventilation

EnergyPlus provides several control strategies to manage ventilation in a way that is consistent with modern HVAC controllers, CAV and VAV installations. It is possible to program a full functioning controller into RadTherm; however this would take significant amount of time and would depart from the scope. Instead, the controls are pre-determined and a specific ventilation schedule implemented. The ventilation rate is based on suggested ASHRAE 60.1 guidelines to provide 2.5 L/s per person and 0.3 L/s per m^2 of floor space, resulting in an volumetric flow rate of 41.7 L/s during occupied and 27 L/s during unoccupied hours. (ASHRAE 2007)

With specific flow rates and occupancy schedules known, a curve can be created for RadTherm that controls the flow rate of air between nodes. Using the same Excel based schedule generator as the internal gains, an hourly ventilation curve is created based on selected dates and if those days are weekdays, weekends or holidays. The indexed curves for weekdays and weekends are shown in Figure 4.4 below. The index is multiplied by the maximum ventilation rate to the desired rate for a specific time step. Holidays are assumed to be times when there are no occupants and mechanical ventilation is thus turned off.

Figure 4.4 – Ventilation flow rate curves in L/min (default SI unit in RadTherm)



4.4.2 Heater & Chiller

Real world HVAC controllers are forced to operate solely on the measurements they can read. In a simulation, far more information is known about the building and thus can be used to solve for heating rates. While it would seem disingenuous to use an unrealistic controller, real world controllers have the advantage of sampling data at intervals much shorter than the simulation time steps and the characteristic time of the zone. The feedback from readings result in a steady state or slowly oscillating zone condition, assuming the heater and chiller are sized appropriately. (U.S. DOE 2011, p.8)

The steady state heating/chilling condition can be simulated in RadTherm by solving the heating or cooling rate based on the heat balance of the room. The air in the room is assumed to be perfectly mixed, thus having the same temperature throughout. The heat balance is represented visually by Figure 4.3 above and the equation;

$$C_z \frac{dT_z}{\delta t} = \dot{E}_G + \dot{E}_C + \dot{E}_S + \dot{E}_I + \dot{E}_M$$ Equation [4]

$C_z\, dT_z/\delta t$ = energy stored in the zone air per time step (J/s)

$\dot{E}_G$ = heat transfer rate from internal gains (W)

$\dot{E}_C$ = convective heat transfer rate from surfaces (W)

$\dot{E}_S$ = heat transfer rate of the system (W)

$\dot{E}_I$ = heat transfer rate due to infiltration (W)

$\dot{E}_M$ = heat transfer rate due to mixing with other zones (W)

Since the study model is only a single zone, there is no heat transfer due to mixing with other zones ($\dot{E}_M$=0). In the RadTherm model, the heat rates of the internal gains ($\dot{E}_G$) and the convection from surfaces ($\dot{E}_C$) can be read directly from the thermal solver. In reference to Figure 4.3 above, the solar, conductive and radiant internal gains are all read from the convective heat transfer term of the interior surfaces in RadTherm.

The heat rate due to infiltration can be calculated with values supplied by RadTherm, and is represented by the equation;

$$\dot{E}_I = \dot{m} \times c_p (T_\infty - T_z)$$ Equation [5]

$\dot{m}$ = mass flow rate of the infiltration (kg/s)

c_p = heat capacity of the air (J/kg-K)

T_∞ = ambient air temperature (°C or K)

T_z = zone air temperature (°C or K)

The energy stored in the zone air node has two primary components, C_z and $dT_z/\delta t$. C_z is the total heat capacity of the zone air mass (J/K), which is a combination of the density (kg/m^3), volume (m^3) and heat capacity (J/kg-K). $dT_z/\delta t$ is the partial differential representing the change in temperature between time steps (K/s). EnergyPlus contains two models to represent the partial differential; a first and a third order finite difference approximation. The first order equation is shown in Equation [6], and the third order equation shown in Equation [7] below. The first order, or Euler formula, uses the zone temperature one time step in the past and tends to become unstable with longer time steps. The third order approximation was developed as a solution to the time step problem, and is now the default solver in EnergyPlus. It uses the zone temperature of three prior time steps. There is a third analytical solver which uses a “predict and correct” method, which will not be discussed here.

$$\frac{dT}{dt} = \frac{T_z^t - T_z^{t-\delta t}}{\delta t} + O(\delta t)$$ Equation [6]

$$\frac{dT}{dt} \approx \frac{\frac{11}{6} T_z^t - 3T_z^{t-\delta t} + \frac{3}{2} T_z^{t-2\delta t} - \frac{1}{3} T_z^{t-3\delta t}}{\delta t} + O(\delta t^3)$$ Equation [7]

A primary difference between RadTherm and EnergyPlus in respect to the HVAC model is that EnergyPlus is simultaneously solving the room temperature with heating/cooling load, while RadTherm has a separate thermal solver. The RadTherm HVAC model is piggybacked on to determine the heater power necessary to maintain the set point temperature, therefore T_z at time t in Equation [6] and Equation [7] is actually the set point temperature, not the numerically solved zone temperature. A test of each equation in RadTherm shows no advantage to using Equation [7] over Equation [6] for stability. The only difference is a slightly larger dT/dt coefficient and thus a translated heater curve by the same amount. The control represented with Equation [6] is used for RadTherm in this study, and the final component needed to find the heater/chiller power, $\dot{E}_S$.

The heater/chiller power as defined in Equation [4] is the sensible heat required at the zone. The power required from the heater to supply the zone sensible heat is greater when ambient air is lower than the zone temperature, and can be solved using the sensible power demand. The zone sensible heat rate is defined by the equation;

$$\dot{E}_s = \dot{m} \times c_p(T_h - T_z) \qquad \text{Equation [8]}$$

$\dot{m}$ = mass flow rate of the mechanical ventilation (kg/s)

c_p = heat capacity of the air (J/kg-K)

T_h = heater supply temperature (°C or K)

T_z = zone air temperature (°C or K)

From Equation [8], T_h can be determined and then used to find the required heater power, defined by the equation;

$$\dot{E}_H = \dot{m} \times c_p(T_h - T_{he}) \qquad \text{Equation [9]}$$

$\dot{m}$ = mass flow rate of the mechanical ventilation (kg/s)

c_p = heat capacity of the air (J/kg-K)

T_h = heater supply temperature (°C or K)

T_{he} = temperature of the air supplied by the heat exchanger (°C or K)

With the heater power now determined, it is imposed to the geometry-less air node representing the heater. It is fed air from an advection link connected to the heat recovery air node, and delivers air through an advection link to the zone air node. This test was run without the heat recovery model, in which case $T_{he} = T_\infty$.

4.4.1 Heat Recovery

While a full heat recovery model has been constructed in RadTherm, there is a discrepancy issue that has caused it to be abandoned. First, the calculated temperature (and thus power rating) are much higher than what EnergyPlus is calculating. DesignBuilder only reports the power rating of the heat exchanger, which is easily back calculated to determine the output temperature. The output temperatures are 8-10°C less than what is calculated in the RadTherm model. This issue is unexpected since the equations are based on EnergyPlus documentation. Further research into the physics of heat recovery systems could reveal the cause of the discrepancy; however this would deviate from the scope and is not possible in the given time. A full description of the model is supplied in Appendix B.

4.5 Convection Coefficients

EnergyPlus comes with a large library of algorithms to calculate convection coefficients with, enough so to have an algorithm built simply to select the appropriate convection algorithm for a given condition. RadTherm does not come with any built in convection algorithms for interior surfaces, but does for wind swept exterior surfaces. Curves and routines can be applied to the convection coefficient if a dynamic response is required. In the interest of time, the interior convection coefficient is left as a constant 5 W/m^2-K for all surfaces.

For the exterior surfaces, the “simple combined” algorithm from EnergyPlus is used and then matched in RadTherm. The method uses a linear relationship with wind speed as the variable and the surface roughness to determine the constants. RadTherm offers three wind convection models, one of which is a linear relationship that matches EnergyPlus. RadTherm does not take into account the roughness of individual parts, but does allow custom input of constants for use in the equation. To determine the appropriate constants, the convection coefficients for siding and window glass are calculated for wind speeds between 0 and 10 m/s. For each speed, the average is taken and plotted. Since RadTherm uses the same equation for all wind swept surfaces, the coefficients are selected such that they match the resultant average curve. The final equation used for calculating exterior convection coefficients in RadTherm is shown below;

$$h = 5.02 + 1.767V \qquad \text{Equation [10]}$$

V = wind velocity (m/s)

5 Mesh Resolution Test

It is very common in meshed based simulations to minimize the number of facets required in an attempt to speed up the simulation time. The trade-off is a potential loss of accuracy as the mesh density is reduced. Very large transient RadTherm simulations can sometimes require many hours or even days to fully solve. With an objective to run a transient simulation of one year, keeping the facet count (and subsequently the thermal node count) to a minimum is critical to achieve a pragmatic modeling technique.

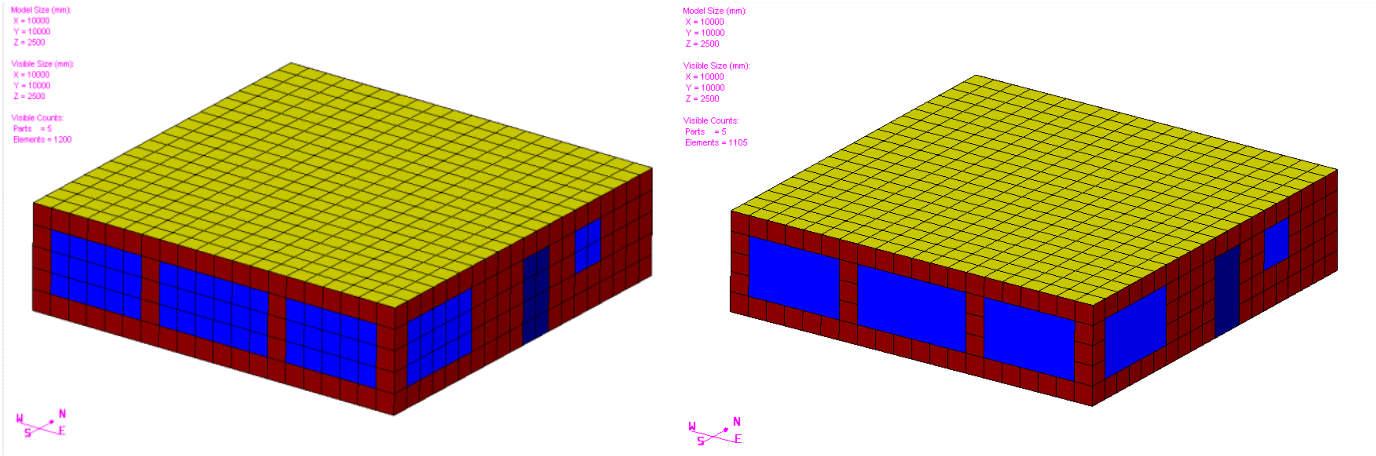
To simplify and help standardize the meshing process, the geometry in RadTherm is created using it's built in geometry tools. All facets are perfectly square and the sizes, facet counts and thermal node counts are listed in Table 5.1 below. In addition, a technique to explore the possibility of selective mesh reduction is tested. In all of the same traditional mesh sizes, the window and door parts are replaced with a single mesh. The percent reduction in counts is around 8-9% and can also be seen in Table 5.1.

Table 5.1 – Mesh sizes and facet, thermal and radiation node counts

	Traditional Mesh			Single Facet Windows			Count Reduction		
Mesh Sizes (cm)	**50 x 50**	**25 x 25**	**10 x 10**	**50 x 50**	**25 x 25**	**10 x 10**	**50 x 50**	**25 x 25**	**10 x 10**
Facets	1200	4800	30,000	1105	4390	27,385	7.92%	8.54%	8.72%
Thermal Nodes	6790	27,142	169,606	6234	24,744	154,314	8.19%	8.84%	9.02%
Radiation Nodes	2400	9600	60,000	2210	8780	54,770	7.92%	8.54%	8.72%

Replacing the windows and doors with a single facet results in two primary differences from the traditional model; the single facet can no longer capture 2-D temperature gradients, and there can be no lateral conduction between the windows/door and the walls. The 2-D temperature gradients could be a potential concern depending on the nature of the study, i.e. if external shading were being explored. In this study, the loss of detail is negligible. The loss of conduction is due to the thermal solver requiring matching node point locations along the edges of two parts. However, even in a fully meshed window, the recommended technique from TAI is to break the conduction between the windows/door and the wall. This accounts for the thermal break in the frame and any insulating material placed in the voids around the frame, which are typically not modeled explicitly in RadTherm. So the move to a single facet has no bearing on conduction modeling. A screen shot of each building model is shown in Figure 5.1 below; with a traditional mesh on the left and a single facet window model on the right (both have a 50cm x 50cm base mesh size).

Figure 5.1 – RadTherm screenshots of a traditional mesh and the single facet windows and door



```
Model Size (mm):
 X = 10000
 Y = 10000
 Z = 2500

Visible Size (mm):
 X = 10000
 Y = 10000
 Z = 2500

Visible Counts:
 Parts    = 5
 Elements = 1200
```

```
Model Size (mm):
 X = 10000
 Y = 10000
 Z = 2500

Visible Size (mm):
 X = 10000
 Y = 10000
 Z = 2500

Visible Counts:
 Parts    = 5
 Elements = 1105
```

To ensure that the model is being tested under a full variety of conditions, testing is done during the winter and summer design weeks. These weeks are defined as the coldest and hottest weeks of the year, respectively. In Stockholm, the winter dates are January 18th-24th, and the summer dates are July 19th-25th. As mentioned in detail in the Methodology chapter, the criteria for measuring the curve fits between EnergyPlus and RadTherm are; total energy difference (in percent), the correlation coefficient, and the normalized root mean square difference (in percent). In each case, the curves are being compared against EnergyPlus, and never against each other.

5.1 Winter Design Week

Shown in Table 5.2 below are the results of the winter design week. As expected, the simulation run times increase considerably with decreased mesh size, and are not a linearly proportional relationship. As node counts increase, the simulation times increase at a faster rate. Also expected is the reduction in run times for the single facet windows. Interestingly, the reduction in run time does not match the reduction in thermal nodes. In the case of the 50x50 and 10x10 sizes, the reduction is 15.69% and 16.01%, respectively, while in the 25x25 size the reduction is 9.30%.

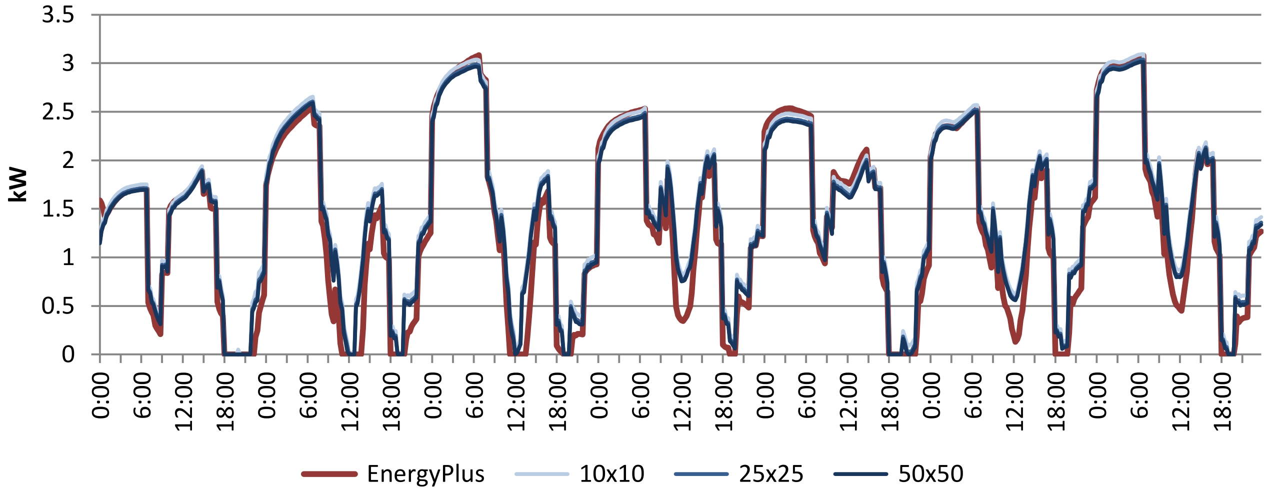
Table 5.2 – Results for the winter design week

	Traditional Mesh			Single Facet Windows		
Mesh Sizes (cm)	**50 x 50**	**25 x 25**	**10 x 10**	**50 x 50**	**25 x 25**	**10 x 10**
Time (s)	325	1409	20,275	274	1278	17,028
Total Energy Difference	6.27%	8.32%	12.69%	6.17%	7.62%	11.16%
Correlation Coefficient	0.9875	0.9870	0.9855	0.9876	0.9872	0.9860
Normalized RMS Difference	6.24%	6.67%	7.84%	6.21%	6.51%	7.41%

In every case, RadTherm is predicting higher heating demand than EnergyPlus. The most surprising result is the significant increase in total energy difference as the mesh resolution increases. This is typically the opposite of what would be expected. Correlations remain basically constant and, like the total energy the normalized RMS difference increases with mesh resolution. Interestingly, the single facet window models performed nearly identical to the traditional, even slightly better. In every case, the RadTherm models meet the minimum performance limits.

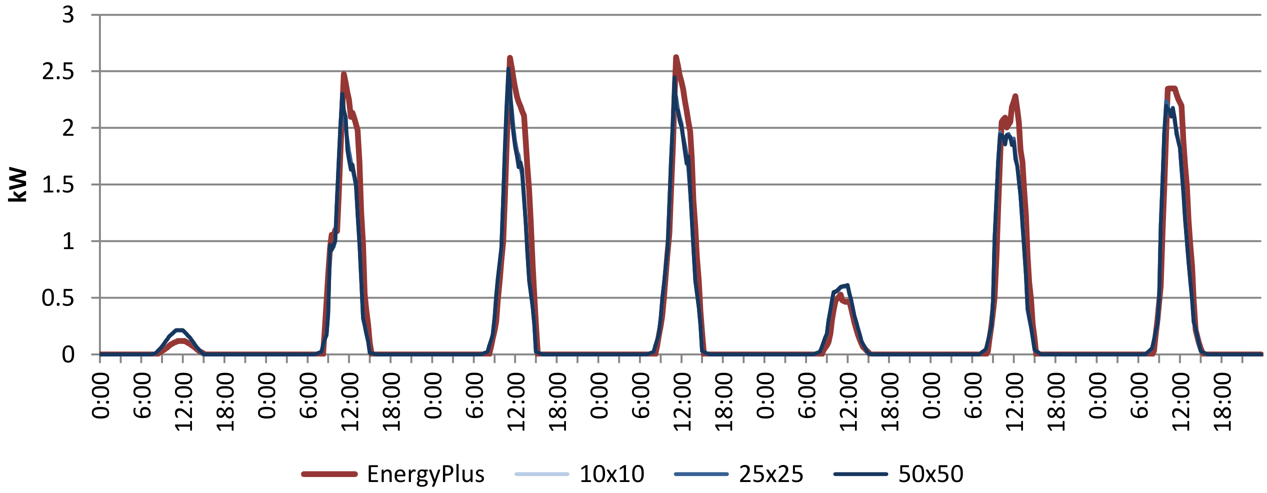
While performance numbers are helpful for quantifying the data, the power curve can show where the differences occurred. Shown in Figure 5.2 below is the power rating curves for the heater in each test case during the winter design week. EnergyPlus stands out in red, while all of the RadTherm curves are shown in thin, blue lines. It is difficult to see here, but the difference in each RadTherm curve is essentially a translation vertically on the y-axis.

Figure 5.2 – Winter design week heater power, single facet window



Over the course of the week, there are two times of day when RadTherm consistently deviated from EnergyPlus; at night (19:30-22:00) when internal gains dropped off significantly, and midday (11:00-13:00) when solar radiation gains peak. In every simulation internal gains were checked to ensure a match, so the difference here is due to the internal workings of the thermal solvers and could not be investigated. The solar gains can be reviewed however, and plotting of the data shown in Figure 5.3 reveals a discrepancy.

Figure 5.3 – Winter design week solar gains, single facet window

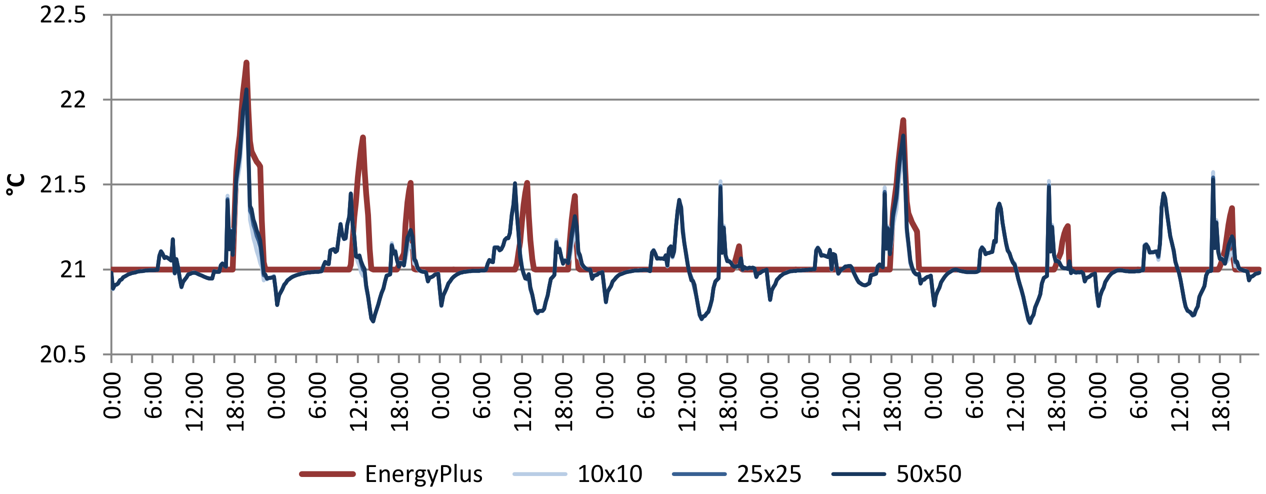


On days when direct solar radiation levels are highest, RadTherm shows a significantly lower gain than EnergyPlus. Interestingly, the deviations are very pronounced and occur at very specific times. The cause of the deviations could not be explicitly determined, however there are two known discrepancies between the models worth noting; first is the solar position and the second is the way solar gains are reported. RadTherm is capable of being given solar positioning data or can model position on its own. The solar positioning data used by EnergyPlus could not be located, and therefore RadTherm used its own positioning algorithm. The differences are very slight however, and are likely not be enough to cause such a large difference. The solar gains in RadTherm are reported by reading the solar radiation received by the interior surface of all parts. Given EnergyPlus' ability to distribute solar radiation in a variety of manners, it is speculated that it is reading solar gains as a function of radiation passing through the window areas. No conclusion can be made on if this difference is significant either, and the discrepancy will have to be left to further research.

It should be noted here that there is another known discrepancy in the solar data that was resolved at a later date. The error proved to have an insignificant effect on the results and is discussed in detail in the Corrections chapter.

To monitor that the conditions inside the building remain consistent between each model, interior temperatures have also been tracked and plotted, as seen in Figure 5.4 below. The average temperatures are almost exactly the same (within 0.02%) however it is clear that there is a limited correlation between the curves. The RadTherm temperature rises and dips below the set point daily, which shows that it lags when compensating for changes in interior or solar gains. This is due to the RadTherm HVAC model being external from the thermal solver, whereas the two are integrated in EnergyPlus and thus a very steady temperature is possible so long as the HVAC unit is capable. This is mentioned briefly in the Heater & Chiller section and will be discussed in detail in Discussion chapter.

Figure 5.4 – Winter design week interior air temperatures, single facet window



5.2 Summer Design Week

Included in this section are all of the same data provided for the winter case. In Table 5.3 below are the statistical results of the simulations. In a similar fashion, the simulation run times increase with decreased mesh size and the single facet models run faster. However, in this case the run times decrease by 8.23%, 14.52% and 15.23% for the 50x50, 25x25 and 10x10 sizes, respectively. While this pattern may have better correlation with the node counts, no conclusions can be made given the same uncontrolled background process variable present in the winter case.

The data shows that the RadTherm model matches EnergyPlus considerably better in the summer. The difference in total energy is within 1% in all cases, the correlations are better and the normalized RMS is roughly half. As in the winter case, the replacement of the window and door mesh with a single facet had a negligible difference on the accuracy of the simulation. Interestingly, while the change improved the results once again, it did so in conditions where RadTherm was both over and under estimating total energy.

Table 5.3 – Results for the summer design week

	Traditional Mesh			Single Facet Windows		
Mesh Sizes (cm)	**50 x 50**	**25 x 25**	**10 x 10**	**50 x 50**	**25 x 25**	**10 x 10**
Time (s)	316	1681	21,050	290	1437	17,844
Total Energy Difference	0.84%	0.48%	-0.27%	0.80%	0.47%	-0.21%
Correlation Coefficient	0.9945	0.9943	0.9947	0.9945	0.9944	0.9948
Normalized RMS Difference	3.55%	3.58%	3.44%	3.53%	3.55%	3.38%

In reviewing the summer case power curve data, shown in Figure 5.5 below, the RadTherm curves are much more consistent with each other, and only have considerable deviations from the EnergyPlus curve during midday. Once again RadTherm requires more input energy during that time, and upon review of the solar data, shown in Figure 5.6, this is consistent with greater solar gains. Again, the cause of the difference could not be determined and can only be noted for future work.

Figure 5.5 – Summer design week chiller power, single facet window

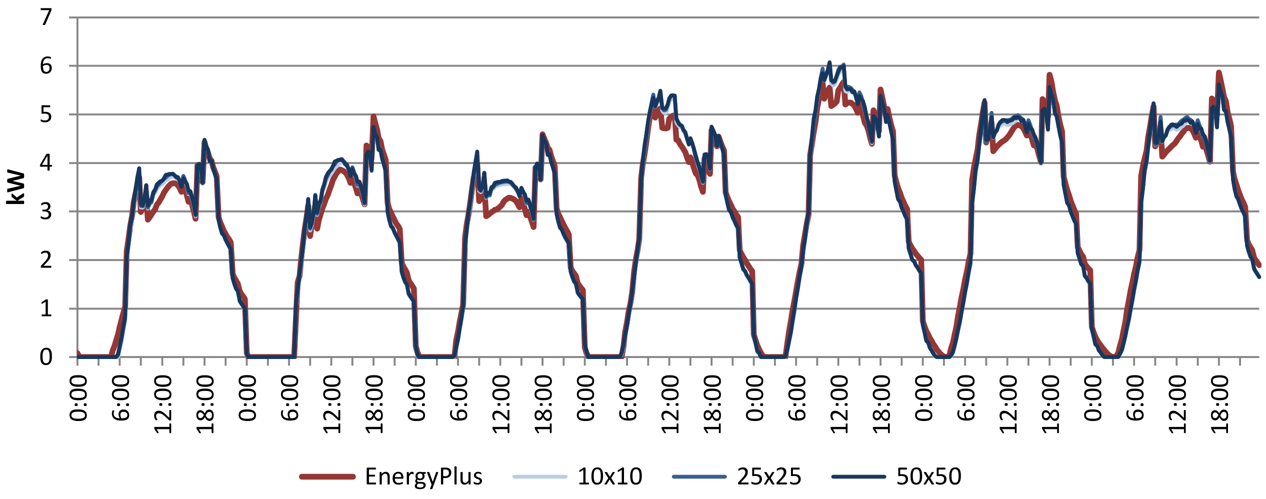
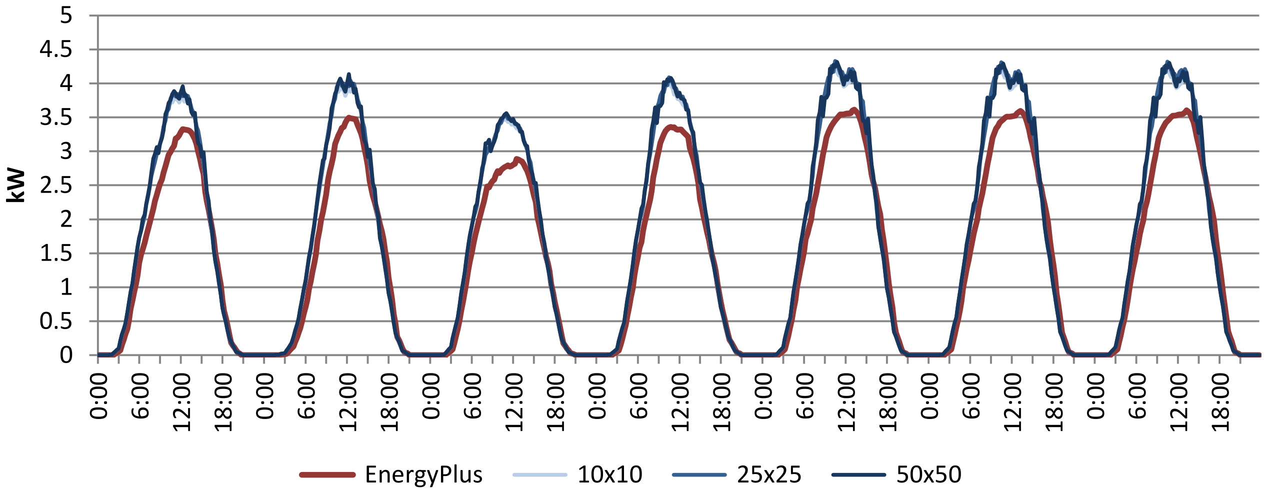
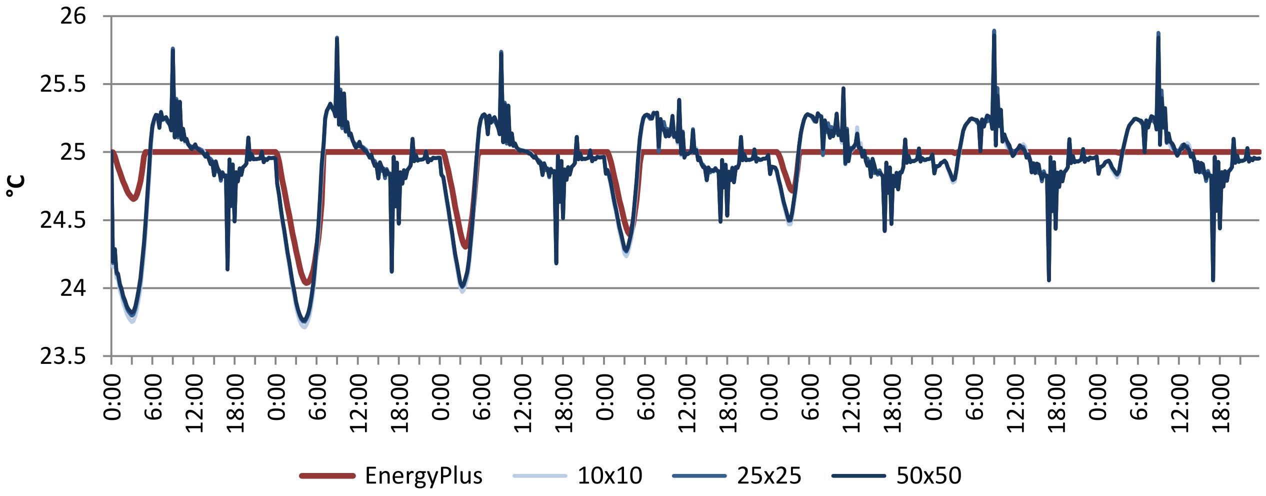


Figure 5.6 – Summer design week solar gains, single facet window



Reviewing the interior temperature, again RadTherm is attempting to adjust for the transient conditions. While present in the winter case, more noticeable here are the large spikes occurring at 09:00 and 17:00 each day. This is due to the change in ventilation rates. What appears to be happening is the heater or chiller power does not coordinate with the change in air flow. With more dedicated development work this spike could be removed, however because the effect is negligible for this study the error has been left in place.

Figure 5.7 – Summer design week interior air temperatures, single facet window



5.3 Conclusion

Through a testing many mesh variations of the RadTherm model, it is shown that decreasing the mesh size considerably increases the run time and replacing window and door mesh with single facets has no significant effect on the accuracy of the model relative to EnergyPlus. In the winter case, the 50cm x 50cm, single facet window model was actually the most similar. The natural inclination then is to use the fastest running model for performing the annual simulations, which is the 50cm x 50cm size, single facet window model.

6 Annual Simulation Methodology

The Mesh Resolution Test shows that the facets can be very large, minimizing simulation time, and the model used in this study will be the 50cm x 50cm mesh size with the windows replaced with a single facet. This portion of the study seeks to find a modeling methodology that can reduce simulation times without sacrificing excessive accuracy. In addition to running a full scale annual simulation model, there are two abbreviated techniques tested; the *day per week* and *day per month* methods. Both techniques run on the same principle, where a weather file is created with the average conditions for each hour combined into a single day. This average day then represents every day over the time period. In the weekly case, the 52 weather files and models are created and each model represents the averaged seven days. In the monthly case, 12 weather files and models are created and each model represents the appropriate month. In every simulation, the time step length remains 0.25 hours and the data is output every hour on the hour.

6.1 Results

Table 6.1 below show the run time results from each simulation technique. Because the tested methodologies require varying amounts of pre- and post- processing time, the times for thermal solver and processing times are reported separately. As expected, RadTherm requires considerably more time to run its thermal solver compared to EnergyPlus in a full annual hourly simulation. The *day per week* and *day per month* methods can save a large amount of simulation time, 87.8% and 97.1% respectively. However, there is a significant increase in the amount of processing time required which reduces the advantage and in the case of the *day per week* method actually takes longer. This is important because processing time is user time and thus very valuable, whereas thermal solver time is less valuable machine time.

Table 6.1 – Annual simulation run time results from each simulation technique

	EnergyPlus	**Annual Hourly**	**Day per Week**	**Day per Month**
Thermal Solver (s)	90	15,283	1864	437
Pre & Post Processing (s)	300	300	15,600	3,600
Total Run Time (s)	390	15,583	17,464	4,037
Total Run Time (h)	0.11	4.33	4.85	1.12

Following completion of the simulations, discussions with TAI engineers revealed the opportunity for automation of the processing. By harnessing the automated reporting features built into RadTherm and using a batch run technique, the processing time around RadTherm could be reduced to essentially nothing. Combination of the daily data to create an annual simulation is done in Excel, which could also be programmed with macros and automated. The expected result would be processing times for the *day per week* and *day per month* methods being the same or near the times for the annual hourly simulations, meaning total run times of 0.60 and 0.20 hours, respectively.

The other variable to consider is accuracy, and the results are shown in Table 6.2 below. The full annual hourly simulation in RadTherm matches very well, with every figure being improved over the design weeks alone. Surprisingly, the *day per week* method does not match as well as the *day per month*. Given the higher number of simulations, and thus more localized averaging, the *day per week* method was expected to have lower differences than the *day per month*. It does have a better correlation and less RMS differences than the *day per month* method, which does match expectations. It is also worth noting that both approximation techniques resulted in cooling requirements that are outside of the prescribed 10% limit.

Table 6.2 – Annual simulation accuracy comparison to EnergyPlus

	EnergyPlus	Annual Hourly	Day per Week	Day per Month
Total Heating (kWh)	2784	2823	2972	2844
Difference	-	1.41%	6.76%	2.16%
Total Cooling (kWh)	6238	6511	5303	5550
Difference	-	4.37%	-15.00%	-11.03%
Correlation Coefficient	-	0.9920	0.9098	0.8644
Normalized RMS Difference	-	2.22%	8.94%	12.76%

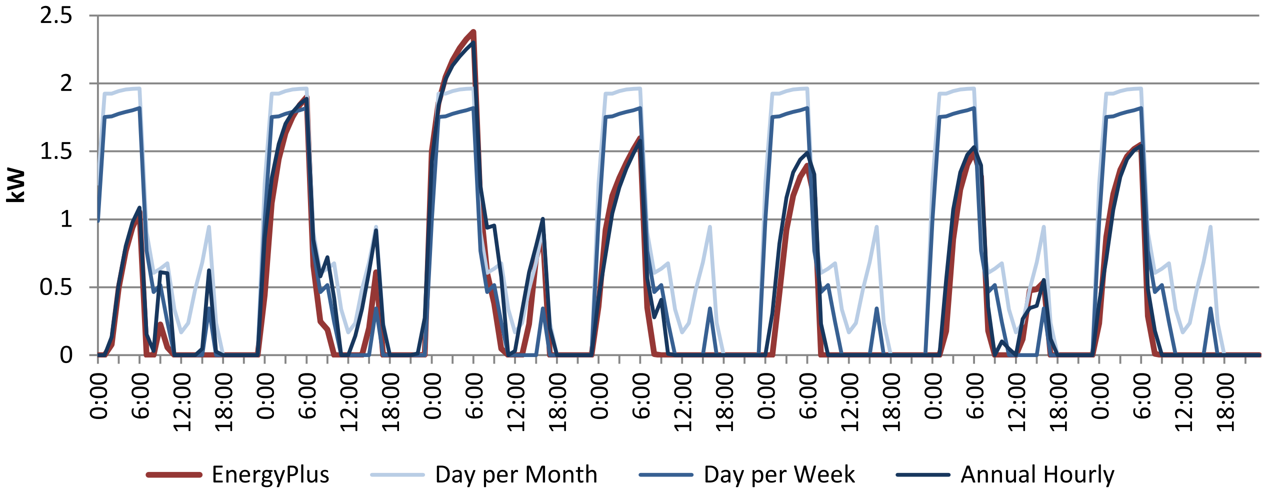
Comparing the approximation results to the full annual hourly RadTherm run is also worthwhile. This comparison is better at showing how the approximation techniques affect the original simulation. The results of this comparison are shown in Table 6.3 below. In each case the difference in total heating is better than when compared to EnergyPlus, but the cooling difference is significantly worse. This is interesting because the approximation techniques only altered the total RadTherm solar gains by 1%, indicating that the hourly loads are more significant that just totals.

Table 6.3 – Annual simulation approximation accuracy compared to RadTherm annual hourly

	Annual Hourly	Day per Week	Day per Month
Total Heating (kWh)	2823	2972	2844
Difference	-	5.27%	0.74%
Total Cooling (kWh)	6511	5303	5550
Difference	-	-18.56%	-14.76%
Correlation Coefficient	-	0.9252	0.8859
Normalized RMS Difference	-	8.45%	12.00%

As indicated by the reduced correlation coefficients, both approximation techniques have less value in the hourly data. Modeling is an iterative process, where errors can be discovered by reviewing the details in results. In the approximation techniques, the details are somewhat muddled and do not tell as good of a story as the annual hourly data. This can be seen in the graphing of week five data shown in Figure 6.1 below. On the first day the temperature is warmer than subsequent days of the week and thus requires less heating, however the averaged techniques don’t capture this and overestimate the load by nearly double. Depending on the objectives of the modeler, this can potentially weaken the usefulness of the approximation techniques.

Figure 6.1 – Comparison of annual simulation techniques during week five (Feb. 5-11)



6.2 Conclusion

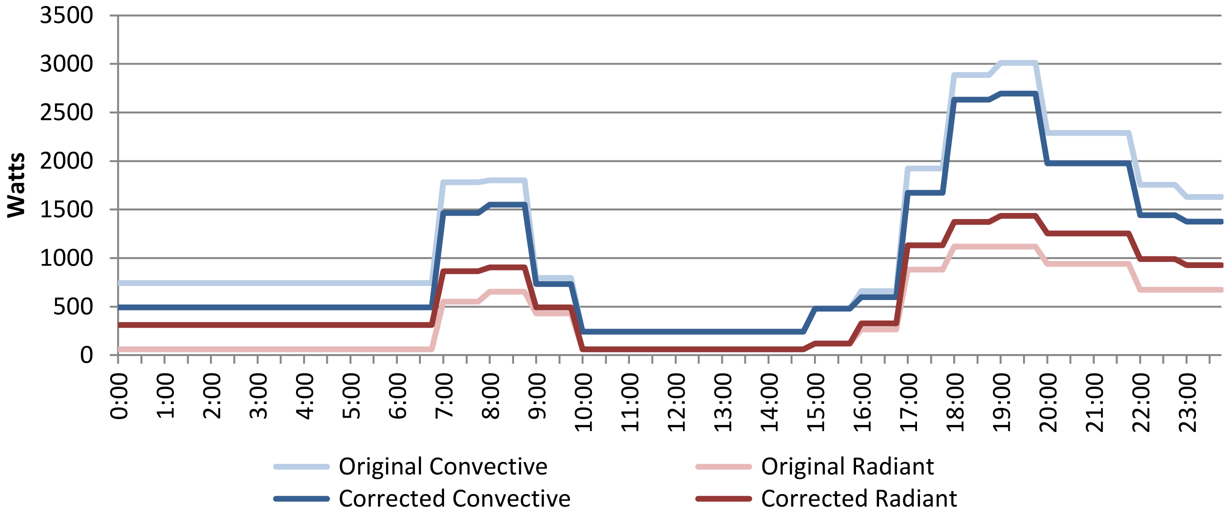
The testing of these two approximation methodologies has shown that there can be a considerable saving of time over running a full annual hourly simulation in RadTherm, however there is also significant loss of information. In both methodologies the total energy for cooling demand exceeds the 10% difference limit from EnergyPlus placed on this study. Additionally, the information which can be read from reviewing graphed hourly data is lost in each approximation technique. The severity of the differences between the approximation techniques and EnergyPlus can be interpreted very differently depending on the objective of the modeler. If the model were in the early stages of development, and the only metric being observed is total energy demand, then the approximation techniques could be valuable. In this case the value of the data is subjective to the modeler and no objective conclusion can be reached. For this study however, the only simulation to meet the tolerance criteria is the *annual hourly* method and thus will be used in the microclimate simulations.

The large gap in cooling energy data must be highlighted and can be traced back to the difference in solar radiation gains. In the full annual hourly simulation, the RadTherm model had 37.4 kWh (9.5%) less solar gain during the heating season, and 129.3 kWh (11.3%) of extra gains during the cooling season. Since the approximation models have less than 1% difference in total solar gain than the annual hourly RadTherm simulation, the hourly solar gain values, and most likely all weather data, are considered to be significant to the simulations and averages cannot accurately replace actual data. This conclusion confirms Crowley's (1998) findings and supports the basis for the TMY weather data. The effect is amplified in the cooling months because of the high seasonal variation in solar radiation in Stockholm.

7 Corrections

After 10 weeks of developing the RadTherm model and running the simulations presented above, it became apparent that there were several noteworthy errors and that they need to be corrected. This chapter reviews the errors and simulation results from the correction models. First is lack of any radiant gains from occupants. Humans radiate approximately 50% of the sensible heat they give off, and thus will have a considerable effect on the convective and radiant curves used in the study. The Excel tool used to generate the curves has been modified, new curves generated and brought into RadTherm. The original and corrected weekday curves are shown in Figure 7.1 below.

Figure 7.1 – Original and corrected interior gains curves



The second error is the use of modeled direct normal solar data in RadTherm rather than measured. This distinction was known during the development of the weather file; however it was originally believed that RadTherm could not accept measured direct normal data. RadTherm can accept measured data, and a revised weather file is created to include it.

The third error is related to convection coefficients and wind speeds. During microclimate development, it was discovered that EnergyPlus is modifying the surface wind speeds significantly from what is read in from the weather file. (U.S. DOE 2011, p.54) Met station anemometers are typically set at 10m above ground level; however buildings can have floors at 1.5m to 1000m above the ground which often have very different wind speeds. A primary cause of this is the condition of the earth's surface, where flat, open plains will have a more constant wind speeds, and hilly, forested or urban terrains will have slower wind speeds near the surface. To account for this, EnergyPlus uses an adjustment equation based on the wind speed reading, the surface conditions at the met tower and the surface conditions at the AOI. A full description of the adjustment equation and surface condition coefficients is available in the Wind Speed section of Microclimate Model Description below.

Met towers are usually located near airports, which are in relatively flat fields and EnergyPlus assumes this by default. There is no method to adjust the surface coefficients or terrain conditions in DesignBuilder, so it is assumed to be the average values of "wooded country." RadTherm does not make the same wind speed adjustments, meaning convection coefficients are calculated using a much higher wind speed than EnergyPlus. Instead of adjusting the wind speed, the correction is done by adjusting the wind convection coefficients. Equation [10] in the Convection Coefficients section above is the final, adjusted equation for the “wooded country” default setting. The original wind convection coefficient equation used in the mesh resolution and annual simulation test for RadTherm is;

$$h = 10.68 + 3.76V \qquad \text{Equation [11]}$$

V = wind velocity (m/s)

The fourth RadTherm error comes from incorrect background temps. The original simulations use the RadTherm default background as the method for setting temperatures under the target building. However, these temperatures are also applied to the surroundings, which in EnergyPlus are set by the ambient dry air bulb temperature. To correct this discrepancy, the default background in RadTherm is set to match the ambient air temperature and the outer surface of the ground floor is fixed to the calculated ground temperatures.

During development of the EnergyPlus microclimate scenes, it was discovered that the background surface properties did not match with RadTherm. The solar reflectance value, the only editable value through DesignBuilder, was set at 0.2 rather than 0.3 as in RadTherm. This value was corrected in DesignBuilder to match RadTherm. This value only affects the summer case, as the winter week is assumed to have snow on the ground and thus a reflectance value of 0.9. However, the EnergyPlus winter case was found to have incorrect ventilations settings in the mesh resolution test, which had lower air changes and lacked variation as shown in the Ventilation section above.

The corrections to each program have been made and have been run through the three simulations from the previous tests; the winter design week, summer design week, and a full annual simulation. The model used is the 50cm x 50cm mesh size with single facet windows. The results from these tests determine the validity of the previous work and if a rerun of all previous tests are required. Times were not considered or recorded since the corrections made are not expected to have a significant effect on the speed of calculations.

7.1 Winter Design Week

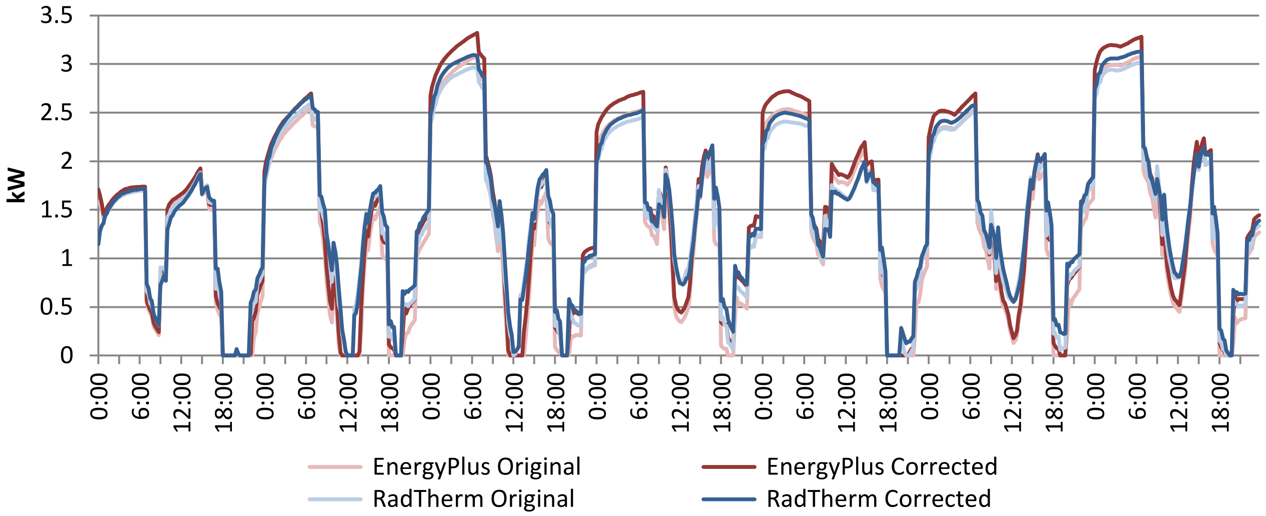
The results from the winter design week in Table 7.1 show that the corrections make a significant difference in the measured parameters, with the total heating demand difference being reduced by over 5%. The correlation is effected very little, and the normalized RMS actually improved slightly.

Table 7.1 – Comparison of original and corrected winter design week results

	Original	Corrected
EnergyPlus Total (kWh)	228.0	250.8
RadTherm Total (kWh)	242.0	253.1
Total Energy Difference	6.17%	0.92%
Correlation Coefficient	0.9876	0.9892
Normalized RMS Difference	6.21%	5.63%

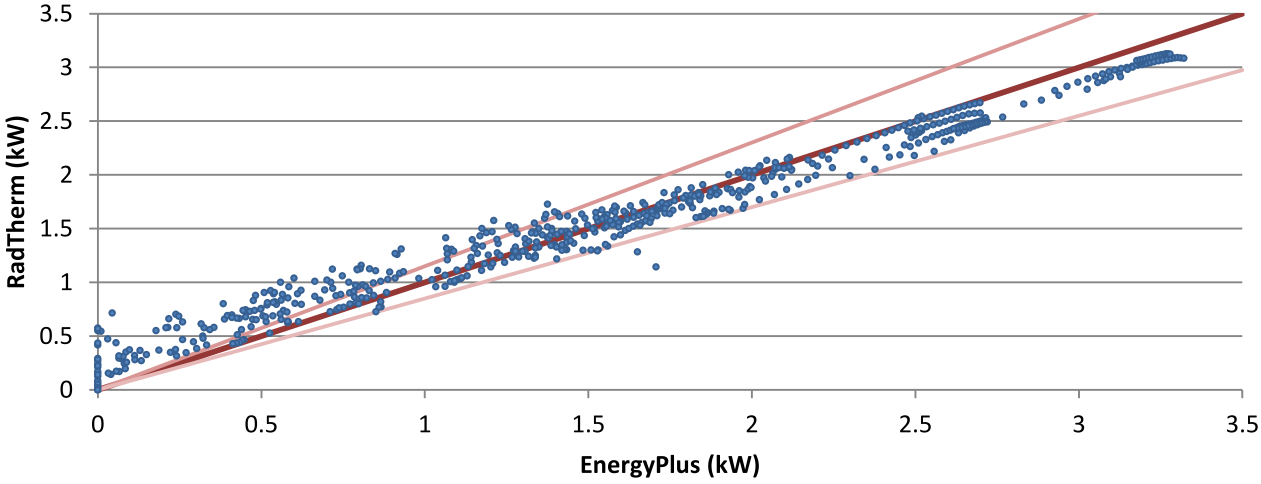
In Figure 7.2 below, the corrected model’s heater power curve is compared against the original and EnergyPlus. The heating demand in EnergyPlus is increased significantly, particularly during the evenings when the heat gains are low and the ventilation error was greatest. The changes in the RadTherm model are less pronounced and without a consistent pattern.

Figure 7.2 – Corrected heater power during winter design week



In addition to the heater curve, Figure 7.3 shows a scatterplot with each model represented on an axis to help identify the appropriateness of the RadTherm model. Each point on the plot is determined by the heater power from each model that are both from a given time step. To identify potential outliers and/or patterns of error, guide lines have been added to the scatterplot. The dark red line represents equal values, and the light red lines are error boundaries set at ±15%. The trend shows that the RadTherm model is over estimating low end heating demands, but is generally acceptable at higher powers. The outliers in the center of the plot are from the initialization of the model, and are not of great concern since this only happens once per simulation and can be minimized with refined seed settings. The general differences could be resolved by understanding the physics behind each of the programs, and is out of the scope of the study.

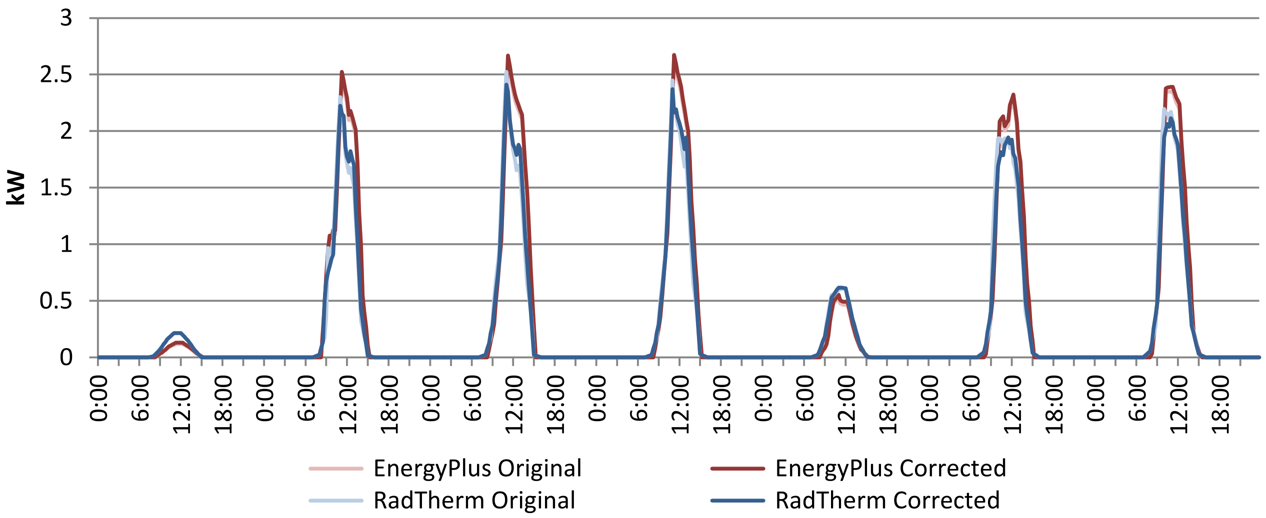
Figure 7.3 – Heater power scatterplot, EnergyPlus vs. RadTherm



The overestimation of heating demand at low power seems to correlate with peak sun and interior gains. Interestingly, the RadTherm heating demand was not significantly altered during midday in the correction, which is where the measured solar data would stand out the most. In a review of the solar gains data, shown in Figure 7.4 below, there is actually very little difference in the corrected model.

This is surprising since the absolute radiation values in the weather file did have a significant difference (±20%) at midday.

Figure 7.4 – Corrected solar gains during winter design week



7.2 Summer Design Week

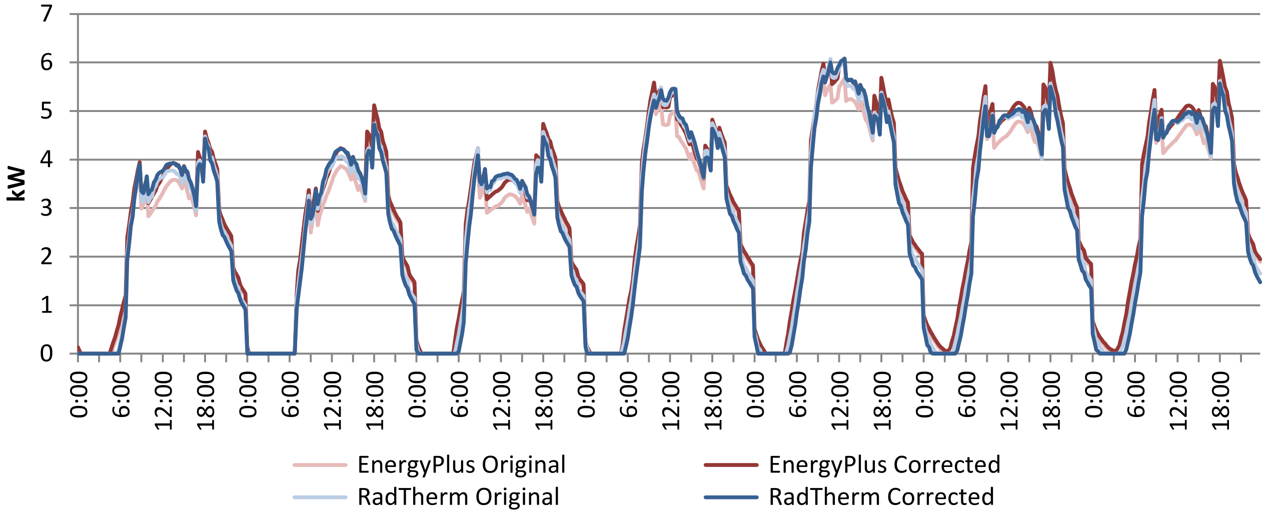
The results from the summer design week in Table 7.2 below show a similar scale of change as the winter week, however in this case the models have become less of a match. The total energy demand in EnergyPlus increased while RadTherm decreased, causing a decrease in the difference by 8%. The correlation is reduced slightly but is still very high, and the normalized RMS increased almost 2%.

Table 7.2 – Comparison of original and corrected summer design week results

	Original	Corrected
EnergyPlus Total (kWh)	456.1	484.9
RadTherm Total (kWh)	459.7	450.1
Total Energy Difference	0.80%	-7.18%
Correlation Coefficient	0.9945	0.9911
Normalized RMS Difference	3.53%	5.44%

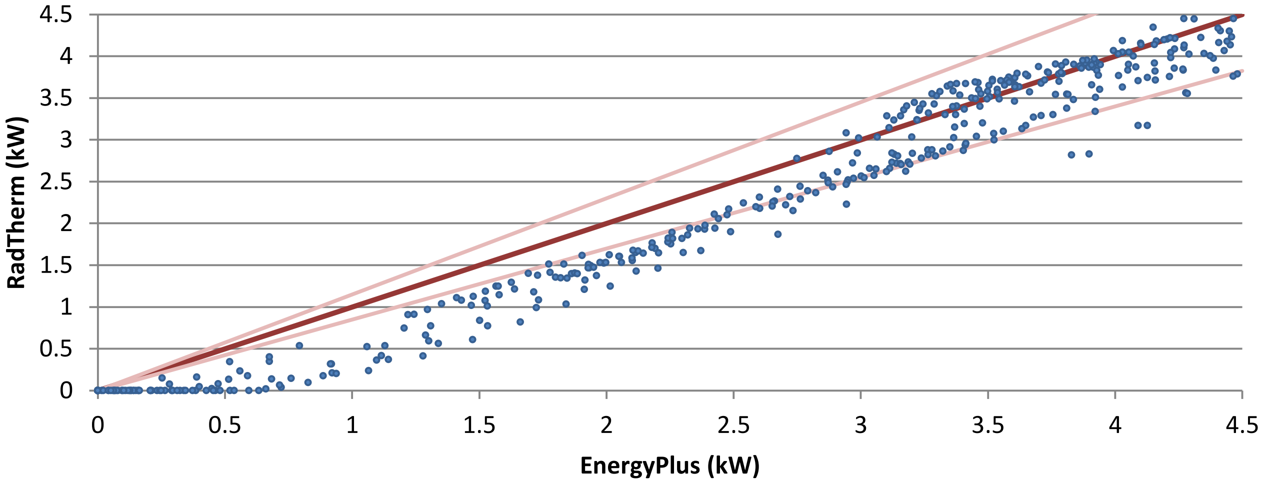
A review of the power curves, shown in Figure 7.5 below, shows a significant increase in demand for the EnergyPlus model during daytime hours. The change to the RadTherm model is less drastic. Interestingly, contradictory to the statistics above the corrected curves appear to be a better match than the originals.

Figure 7.5 – Corrected chiller power during summer design week



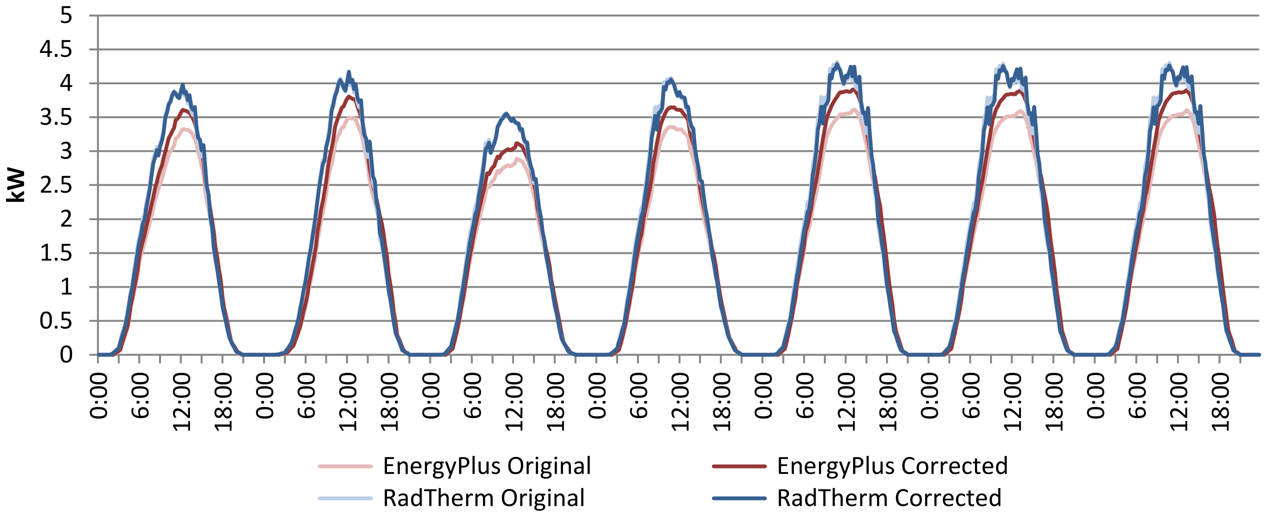
The cooling power scatterplot in Figure 7.6 shows that the RadTherm model is consistently underestimating loads below 3kW. These loads happen during the warm up and cool down hours at the start and end of each day, and suggest that RadTherm may be reacting to the interior gains differently than EnergyPlus. Like the winter case, this is a difference that can only be resolved by understanding the physics behind each of the programs, and is out of the scope of the study.

Figure 7.6 – Cooling power scatterplot, EnergyPlus vs. RadTherm



The solar gains curves in Figure 7.7 below, show that there is little change in the RadTherm data but significant change in EnergyPlus. The increase in solar reflectance results in higher solar gains during midday, explaining the higher cooling loads. This change significantly improved the solar correlation between EnergyPlus and RadTherm.

Figure 7.7 – Corrected solar gains during summer design week



7.3 Annual Simulation

The annual simulation results are shown in Table 7.3 below, and reflect the corrections seen in the design weeks above in that absolute heating demand increases and the cooling demand decreases. The gap between EnergyPlus and RadTherm are slightly larger in both heating and cooling, but still within the specified criteria. Interestingly, the correlation and normalized RMS are a worse match in the correction, but again by negligible amounts.

Table 7.3 – Comparison of original and corrected annual hourly simulations

	Originals		Corrected	
	EnergyPlus	**RadTherm**	**EnergyPlus**	**RadTherm**
Total Heating (kWh)	2784	2823	2818	2981
Difference	-	1.41%	-	5.79%
Total Cooling (kWh)	6238	6511	5841	6161
Difference	-	4.37%	-	5.47%
Correlation Coefficient	-	0.9920	-	0.9859
Normalized RMS Difference	-	2.22%	-	2.91%

7.4 Conclusions

Upon discovery of the errors, there was a concern that all of the prior results could be invalid if the comparisons left the acceptable range. While the changes within simulations were significant, causing as much as a 10% change for a given model, in no case did the comparison values leave the acceptable ranges defined in the Performance Parameters section. Additionally, the corrections being made are unrelated to mesh resolution or simulation methodology, and therefore can be assumed that the results of those tests would yield the same conclusions. Therefore, while the prior data in the Mesh Resolution Test and Annual Simulation Methodology use incorrect inputs, the results are not compromised and the conclusions remain the same. Moving forward in the Microclimate modeling, the 50cm x 50cm mesh with single facet windows will be used as the target building and an hourly time step simulation will be used for annual runs.

8 Microclimate Model Description

In the previous chapters, RadTherm demonstrates the ability to perform annual building simulations with similar results to EnergyPlus. This chapter builds on the single building model with an environment around the target building in which the structures interact with each other and the local air, creating a microclimate. The objective is to create a modeling procedure which is capable of capturing these interactions, demonstrate their significance, and not add impractical amounts of simulation time to the annual case.

Modeling the local climate round the built environment is complex, often involving scene geometry simulated in a thermal solver, and a CFD solver to handle air velocities and/or temperatures and moisture contents. The microclimate model represented here is considerably simpler, still using a high powered thermal solver but relying on simplified convection calculation methodology rather than CFD. The model is built to capture two dominant thermal components typically simplified in annual building simulations; scene component surface temperatures and local air temperature.

The following sections will describe; the additional materials and components added to the model that are not present in the original, construction of the three different scenes being tested, and the algorithms added to represent the microclimate. The scenes are only additions to the original model, meaning the target building has remained the same from the previous chapters and the various environments are built up around it. This is done so that the original models without scenes can be easily compared. Due to the differences between RadTherm and EnergyPlus, there are cases where the scenes and/or components are not identical and are identified as such.

8.1 Scene Components

There are a number of additional components used in the microclimate scenes, mostly made with natural materials. Table 8.1 has a listing of the new materials in use. The only new building material is brick, the properties of which are taken from the DesignBuilder database. The soil and tree bark materials are from the default RadTherm database. While DesignBuilder does have many soil properties, the earthen materials are only being used in the RadTherm model and therefore it was not necessary to correlate the two. The leafy material properties have been determined by a review of several datasets. (Zhang 1999) (Jin and Liang 2006) (Henninger and Witte 2011)

Table 8.1 – Properties of scene specific materials

Material	Conductivity	Specific Heat	Density	Emissivity	Absorptivity	Source
Brick	0.720	840	1920	0.9	0.6	CIBSE
Dry Soil	1	1840	1500	-	-	RadTherm
Dry Sand	3.89	815.88	1505.74	-	-	RadTherm
Tree Trunk	0.074	1260	340	-	-	RadTherm
Tree Leaves	0.15	1100	50	0.98	0.9	Multiple
Grass	-	-	-	0.97	0.75	Multiple

8.1.1 Terrain

Terrain could be considered the foundation of the environmental scene. In RadTherm, there is an ability to create parts that are specifically identified and modeled as *terrain*. These parts then have a default layering structure and can model one dimensional heat and moisture transfer. However, they are incapable of being connected to any air nodes other than the ambient air read in from the weather file. The microclimate model relies on a customized local air node, and for this reason the terrain is constructed as a *multi-layer* part. EnergyPlus does have the ability to model ground features; however these are used for conduction with exterior walls rather than any radiant exchanges. It also gives ground part surfaces the default 0.9 emissivity setting, making them no different than the standard background and thus unnecessary. A non-faceted terrain scene is simulated in RadTherm, and is discussed in detail in the Scene Descriptions section below.

In all of the scenes, the sides of the faceted terrain are 110m by 110m, with a facet size of 2m square. There are three types of terrain that have been created; road, grass and under building. While a traditional terrain part has 13 layers by default, the road and grass parts used in these scenes only have three layers. The layer construction of each part is described in Table 8.2 below. The layering scheme is chosen to minimize the number of thermal nodes in the terrain part, represent reasonable construction and allow matching layers for horizontal conduction. The exposed terrain parts reach a depth of 0.5m, where the temperature is then set by the appropriate temperature curve from Table 4.7. For the road and grass terrains, the 0.5m measured, undisturbed ground temperatures are used.

Since the temperatures under the building are set manually, the under building terrain part is only given one layer. The under building soil is aligned with the second exposed terrain layers for horizontal conduction. It should be noted again that because the part construction is of a *multi-layer* or *standard* part types, and not *terrain*, there is no moisture content or transfer in the soil.

Table 8.2 – Terrain part constructions

Layer	Thickness	Road	Grass	Under Building
Surface (1)	100 mm	Asphalt	Dry Soil	-
2	200 mm	Dry Sand	Dry Soil	Dry Sand
0.5m (3)	200 mm	Dry Soil	Dry Soil	-

For surface conditions, only the road and grass terrain parts have critical values since the terrain under the building is assumed to be in contact with the ground floor. The road surface is specified as asphalt material with asphalt surface properties, but the grass terrain part is somewhat different. The top layer is still soil; however it has been given the surface properties of grass. This approximation is made on the assumption that grass has a negligible thermal mass and to create a more realistic horizontal conduction through the terrain parts. While a number of significant assumptions have been made in the terrain construction, this is the best possible method given the requirements of the microclimate model. Research in ground modeling techniques is increasing, and while a refined terrain model would be applicable to this methodology, identifying such a model is outside the scope of this study.

8.1.2 Buildings

Two of the three scenes include additional buildings around the original target building. To make a realistic scene, the surrounding buildings are assumed to be similar to the target building, and therefore have the same dimensions and nearly the same construction. While it would be possible to simulate the energy consumption of multiple buildings simultaneously, the interior air of the surround buildings is instead fixed to a set point temperature that matches the season (21 for heating, 25 for cooling).

There are two differences between the target building and the surrounding buildings; first, the surrounding buildings use 100mm of brick instead of 13mm of wood as the exterior building material. This is done primarily for the urban scene, where buildings tend to have a masonry exterior and for consistency is brought into the suburban scene. The second difference is that the surrounding buildings do not have any windows or doors, therefore the entire exterior is brick. This is done largely to enable the surrounding buildings to be constructed of 2.5m square facets in RadTherm. Removing the windows could be a potentially large approximation, however it is important to keep the thermal node counts down and keep simulation times to a minimum. Identifying critical features of the microclimate scene is left to future work.

8.1.3 Trees

Accurately capturing the geometry of trees can quickly result in extremely high facet counts and radiation nodes, leading to high simulation times. The trees used in these scenes are intended to represent a typical deciduous tree found in eastern Sweden, such as oak, maple, or birch. They have a 4m high by 4m wide leafy section using 1m square facets sitting atop a 1.5m tall by 0.5m diameter trunk using 0.5m by 0.25m facets. RadTherm uses predominantly surface meshes, so the geometry is represented by two plates that intersect at right angles. A box shape would also work, but the cross shape has a similar shading pattern and requires fewer facets. The trees in EnergyPlus have similar geometry, the difference being that they are volume parts rather than surface and thus have been given a modest thickness of 0.5m. An image of the trees from either program is available in the Suburban and Rural scene descriptions below.

In RadTherm, the construction of the trees has been simplified into two parts; the trunk and leaves. Both parts are of single layer construction described in Table 8.3 below. The leaves are given the surface conditions described in Table 8.1; however the trunk has the original wood surface conditions listed in Table 4.1.

Table 8.3 – Tree part construction

Part	Thickness	Material	Surface
Leaves	2000 mm	Tree Leafs	Tree Leaves
Trunk	250 mm	Tree Bark	Oak Siding

The front and back of the facets have been given the same surface properties on both parts. To capture the thermal and optical behavior of the tree better, some non-standard modifications have been made to the leafy portion. First, to represent a scattered and diffuse leaf pattern it has been set as a transparent material, allowing 10% of light to pass through. Second, since the surface area of the model geometry is significantly less than an actual tree, the wind coefficient multiplier has been increased to five for both the front and back of the part. The leaf thickness is set to 2m in an attempt to capture the thermal mass of the entire leaf and branch matter volume contained in a tree.

8.2 Scene Descriptions

As mentioned above, there are two primary factors being considered when modeling the environment around a building; radiant exchange and local air temperature. In order to identify which features in the microclimate model have the greatest effect, the scenes are built in stages. In the first stage, referred to as *no terrain*, only the above ground objects are added. This creates the most similar simulation between RadTherm and EnergyPlus because the terrain is still represented by the default background. The background will be set with varying surface conditions to match the scene, which is another changed variable from the original single building models. The second stage is called *terrain*, where a faceted terrain is added making the ground a dynamic part of the scene. Finally, the microclimate air model is added which gives the potential for local air temperatures to vary from the ambient, and is referred to as the *microclimate* stage.

There are three environments which the target building has been placed; rural, suburban and urban. These landscapes are quite different in their construction, and have been chosen to represent a wide array of conditions which could affect a building energy simulation. The scenes have been constructed such that the target building view factors should be essentially the same with a larger AOI, making additional facets unnecessary. The faceted terrain underneath all buildings is the same, and is described in the Terrain section above. The three scenes are described in detail in the following sections.

8.2.1 Rural

The rural scene consists of the target building, 36 trees and an all grass terrain. The trees surround the building in two rows, with the first row being 25m away from the exterior walls and the second row 7.5m behind them. The trees are staggered in an attempt to fill the view factors around the target buildings as much as possible to simulate a forest. It would be ideal to fill the terrain out to the edges with trees, but the facet count needs to be kept reasonably low. Screenshots from each program are shown in Figure 8.1 and Figure 8.2 below. The *no terrain* stage in RadTherm is exactly the same except with the faceted terrain parts removed.

Figure 8.1 – Screenshot of the rural microclimate scene in RadTherm

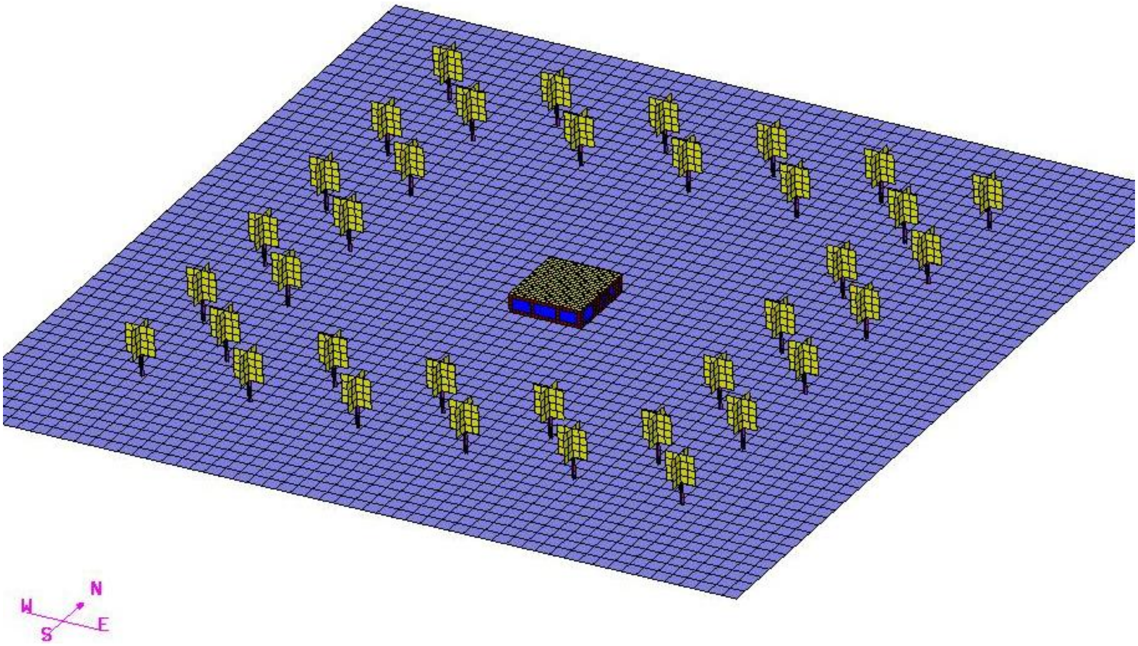
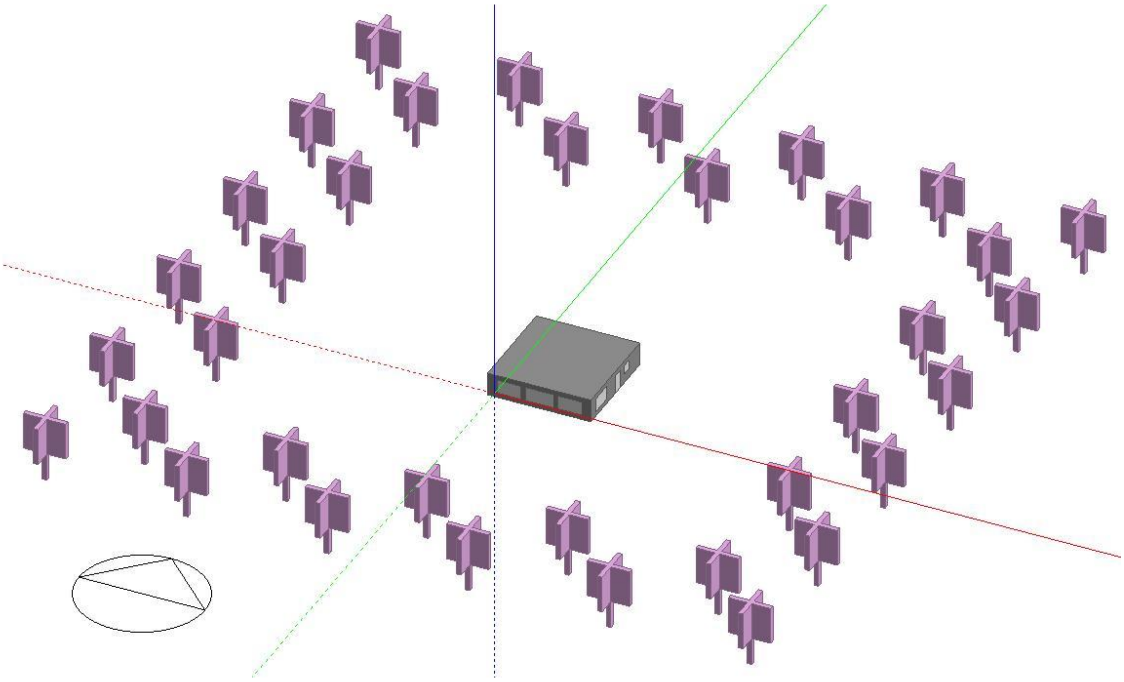


Figure 8.2 – Screenshot of the rural microclimate scene in DesignBuilder



8.2.2 Suburban

The suburban scene is the most dynamic of the three settings. There are nine buildings, 36 trees, and all three terrain types. The buildings are spaced 30m apart and remain in a grid pattern. The surrounding buildings actually sit in the same locations as the outmost buildings from the urban scene. 45 degrees off of each corner of the buildings is a tree, meaning each building has four trees surrounding it. The trees are positioned 4m away normal to the face of the two nearest walls. For 10m in all directions around each building, the terrain is covered in grass. The terrain between each grass lot is asphalt road. The default background can only be set to a single type of surface, and since the terrain closest to the buildings is grass the surface conditions are set to grass. Screenshots of the scene from RadTherm and DesignBuilder can be seen in Figure 8.3 and Figure 8.4, respectively.

Figure 8.3 – Screenshot of the suburban microclimate scene in RadTherm

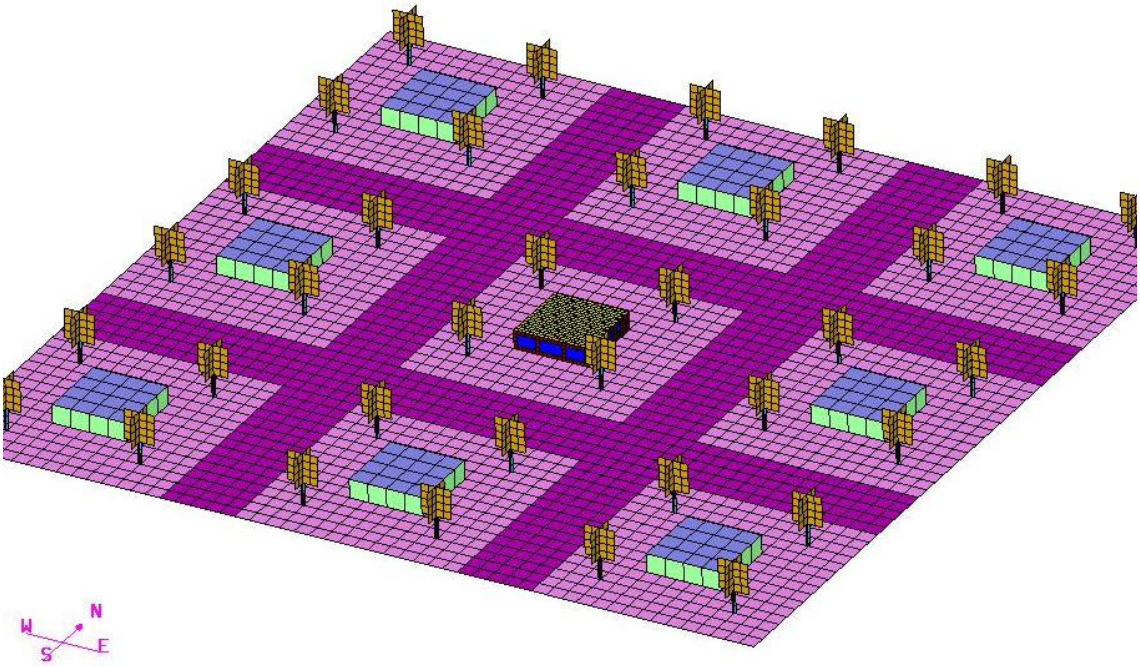
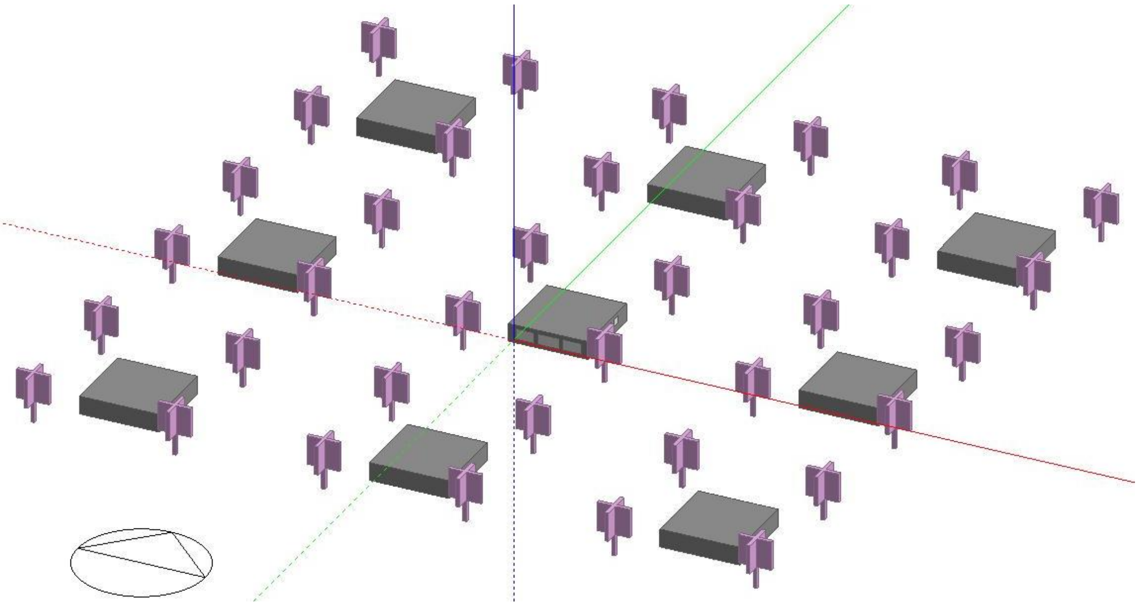


Figure 8.4 – Screenshot of the suburban microclimate scene in DesignBuilder



8.2.3 Urban

In this scene, the target building is surrounded by similar buildings in a dense grid pattern. There are 25 total buildings in the scene with 10m between them. All of the terrain between the buildings is asphalt road, and the default background in both programs is set to the ambient temperature with asphalt surface conditions. Figure 8.5 below is a screen shot of the RadTherm urban scene with the faceted terrain and Figure 8.6 is the screenshot from DesignBuilder.

Figure 8.5 – Screen shot of the urban microclimate scene from RadTherm

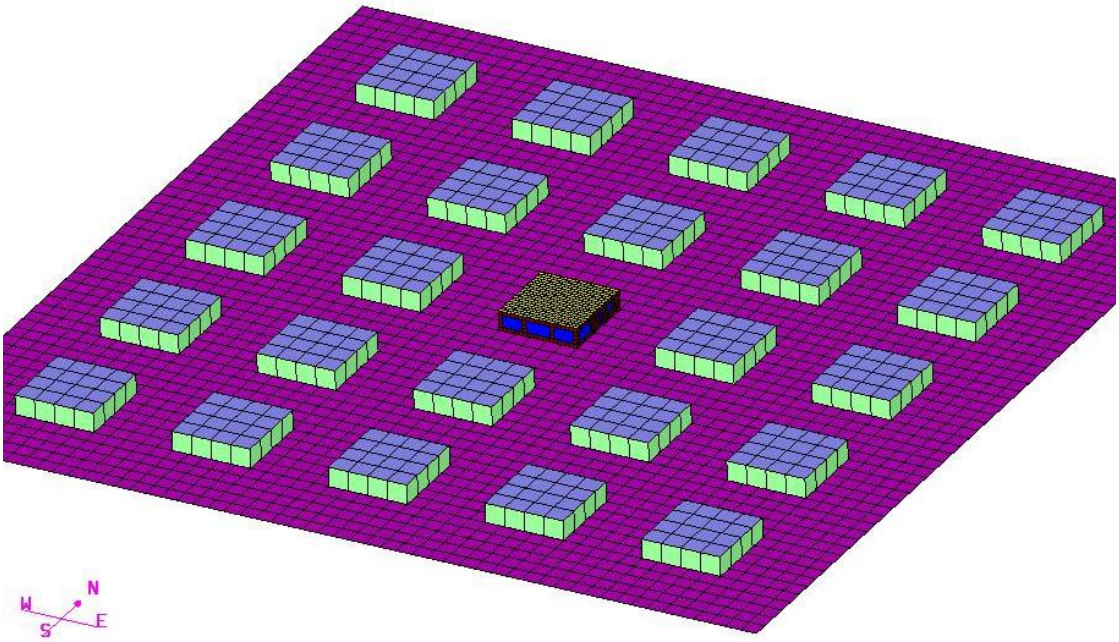
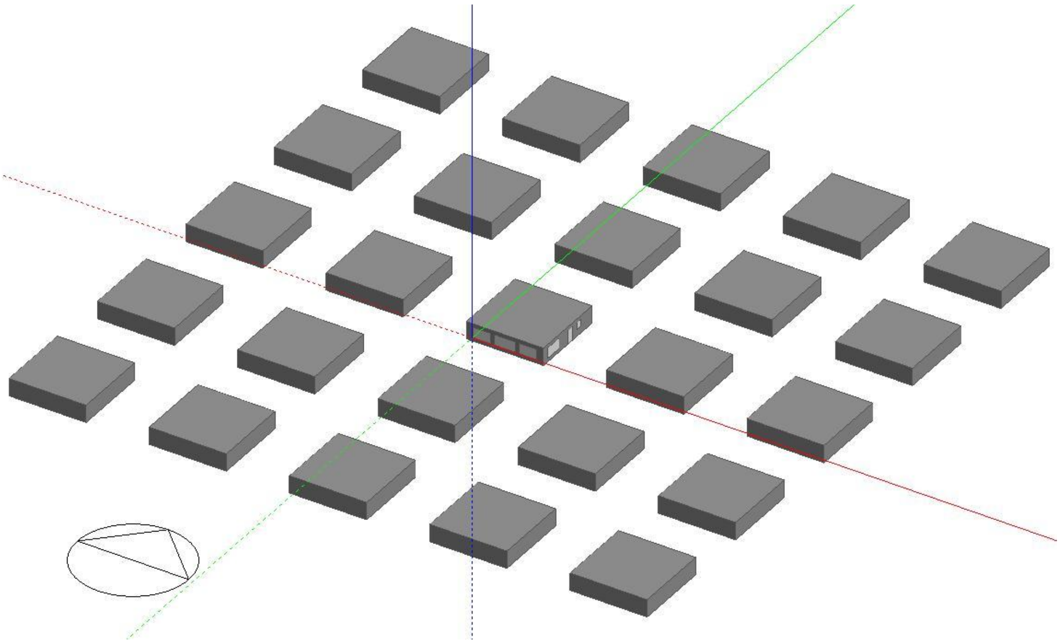


Figure 8.6 – Screenshot of the urban microclimate scene in DesignBuilder



8.3 Wind Speed

Using the correct wind speed for a given location is very important as it has a significant effect on convective heat transfer on a building's exterior. The Corrections chapter first touched on wind speed adjustments for the original model development and the full description of the calculations are listed here. In the *no terrain* and *terrain* stages, where the microclimate air model is not used, the convection coefficient is calculated using the same equation as the original single building models, which is with the original wind speed used in Equation [10].

Only the *microclimate* stage uses actively modified wind speeds, which are then used to calculate the convection coefficient and the air flow through the local air nodes. Wind speed adjustments are driven by; the wind speed reading, the terrain conditions around the met tower, and the terrain conditions around the AOI. (U.S. DOE 2011, p.54) This relationship is described by the equation;

$$V = V_{met}\left(\frac{\delta_{met}}{Z_{met}}\right)^{a_{met}} \times \left(\frac{\delta}{Z}\right)^{a} \quad \text{Equation [12]}$$

V = final wind velocity (m/s)

V_{met} = met tower reading from weather file (m/s)

δ_{met} = depth coefficient at the met tower (m)

Z_{met} = met tower height (m)

a_{met} = surface condition coefficient at the met tower

δ = depth coefficient at site (m)

Z = zone centroid height height (m)

a = surface condition coefficient at the met tower

The surface coefficients for a variety of terrain conditions are listed in Table 8.4 below. The met tower at Stockholm-Arlanda airport, the weather data source used in these simulations, is located in a relatively flat, open field and thus a_{met} = 0.14 and δ_{met} = 270. Met tower anemometers are typically at Z_{met} = 10m above ground level, and Arlanda is assumed to be the same. The terrain conditions for the urban and suburban scenes are expected to match the “Towns/Cities” description best, while the rural scene best matches “wooded country.” The roughness coefficients are adjusted appropriately for each scene.

Table 8.4 – Terrain roughness coefficients for wind speed (U.S. DOE 2011, p.54)

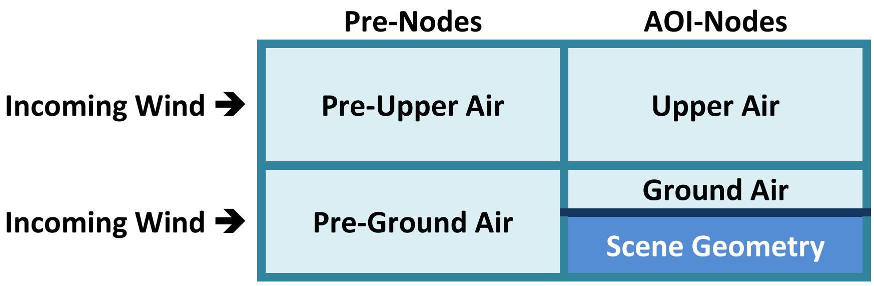
Location	a	δ
Flat Field	0.14	270
Wooded Country	0.22	370
Towns/Cities	0.33	460
Ocean	0.10	210
Urban/Industrial/Forest	0.22	370

Once a local wind speed is calculated, it’s used for setting the convection coefficient for all exterior surfaces as well as the air flow rate for the local air nodes. Since the wind speed has been adjusted, the original equation for calculating convection coefficients (Equation [11]) is used to keep the calculations consistent. The microclimate model uses RadTherm’s routine structure to set the convection coefficient, meaning any method of calculation can now be programmed. This feature is valuable for future work, and is reviewed further in the Discussion chapter. The use of wind speed for air flow rate calculation is discussed in the next section.

8.4 Airflow Management

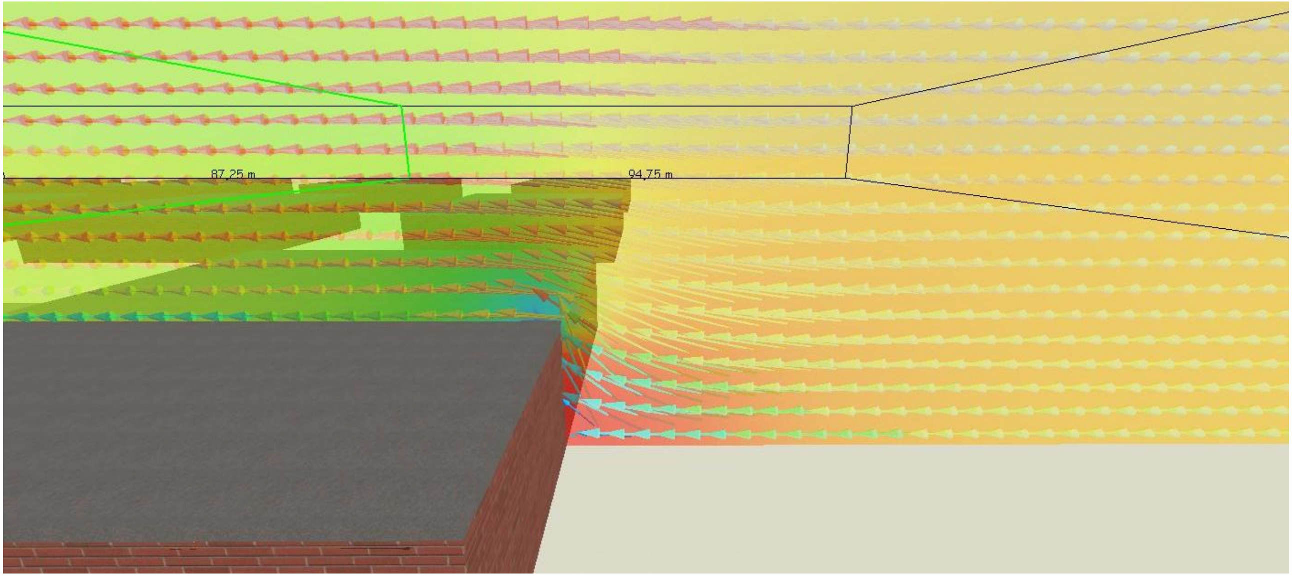
To replace the default wind model in RadTherm, a collection of air nodes connected by advection links are used to represent the local air in the AOI. There are four nodes in total; the air at the ground level in contact with all AOI surfaces, the air volume directly above the ground node, and pre-conditioning air for each node over the AOI. This arrangement with identifying names for each node is represented in Figure 8.7 below.

Figure 8.7 – Physical air node arrangement in the microclimate model



The ground and upper air nodes are to represent only the air that is directly above the AOI, leaving the volume to be set by the heights. In previous CFD work with the built environment, researchers have used a height of six times the tallest object in the scene to ensure capturing all turbulence created by the buildings. (Bouyer, Inard and Musy 2011) A steady state CFD simulation on the urban scene conducted with DesignBuilder (7m/s entry velocity, 0.5m grid), shows free stream air flow within 4m of the roof tops, and only minor disturbances between 1-4m. A screenshot of the first building hit by the wind is shown in Figure 8.8. Therefore, the ground air node height is set at 3m, and the upper air node at 4.5m, giving a total height of 7.5m or three times the height of the buildings.

Figure 8.8 – Screenshot of CFD simulation in DesignBuilder



The air node heights are an important variable in determining air flow. The height of the centroid, 1.5m meters for the ground nodes and 5.75m for the upper nodes, is used in Equation [12] to determine wind speed. The wind speed is then multiplied by the frontal area to determine a volumetric flow rate. For the ground nodes, the frontal area is 110m x 3m = 330m^2. For the upper nodes, the frontal area is 110m x 4.5m = 495m^2. The AOIs are square, meaning the cross-sectional area changes with wind direction, but for simplicity the frontal areas are kept constant.

The volumetric flow rate is calculated at each time step, and is applied to the four advection links: wind --> pre-nodes and pre-nodes --> AOI-nodes. To account for vertical air exchange, advection links are made between the ground and upper nodes over the AOI as well as the pre-nodes. Calculating vertical air flow due to turbulence and buoyancy is complicated and would require a dedicated CFD study or co-simulation to capture, which is outside the scope of this project. As a simplification, the vertical air mixing is set as a constant percentage of volume, in this case 5%.

On its own, the AOI is not large enough to inflict a significant amount of temperature change to the local air. The pre-nodes have been included to condition the incoming air as if it has passed over a stretch of terrain exactly like the AOI, only many times larger. For this study, a multiple of 45 is used. This means the pre-nodes are 45 times larger in volume than the AOI-nodes, and effectively represent 5km of terrain outside the AOI. To condition the air, the net convective heat rate is read from the AOI-nodes, multiplied by 45, and then imposed on the pre-nodes.

An important distinction in this model is that just as with the interior air nodes, the exterior air nodes cannot currently handle latent heat. Therefore, the only sensible heat is considered in this study. This feature is due to be added to RadTherm in mid-2012. A further discussion of the microclimate model limitations is included in the Discussion chapter below.

9 Microclimate Results

The entire microclimate study consists of 27 simulations, including a rural, suburban and urban scene, with simulations run for the winter and summer design weeks, as well as a full annual simulation. For each time frame, there are the *no terrain*, *terrain*, and *microclimate* stages. Just as in the Mesh Resolution Test, the design weeks' heater and chiller curves are graphed to gain a better understand of how the models are reacting. The *annual hourly* method is used for the annual simulations, which will only have statistical data reported. The same Performance Parameters used previously are used here to review each simulation; however in this chapter they are considered a way to measure the differences from EnergyPlus rather than setting boundaries for model acceptance. The results from the single building comparison during BES development are listed as a reference. Additionally, the scene models are compared against the original RadTherm single building model for a direct, intra-program comparison.

9.1 Rural

The rural scene simulations do not show a significant change in energy demand when modeling the microclimate components. During the winter week, there is a general trend towards increasing energy demand with each stage. In the summer, there is an initial reduction in cooling demand which then increases in the *terrain* and falls again in the *microclimate* stage. The annual simulations follow the same trends and as the design weeks, with cooling being affected more than heating. The following sections review the results in detail.

9.1.1 Winter Design Week

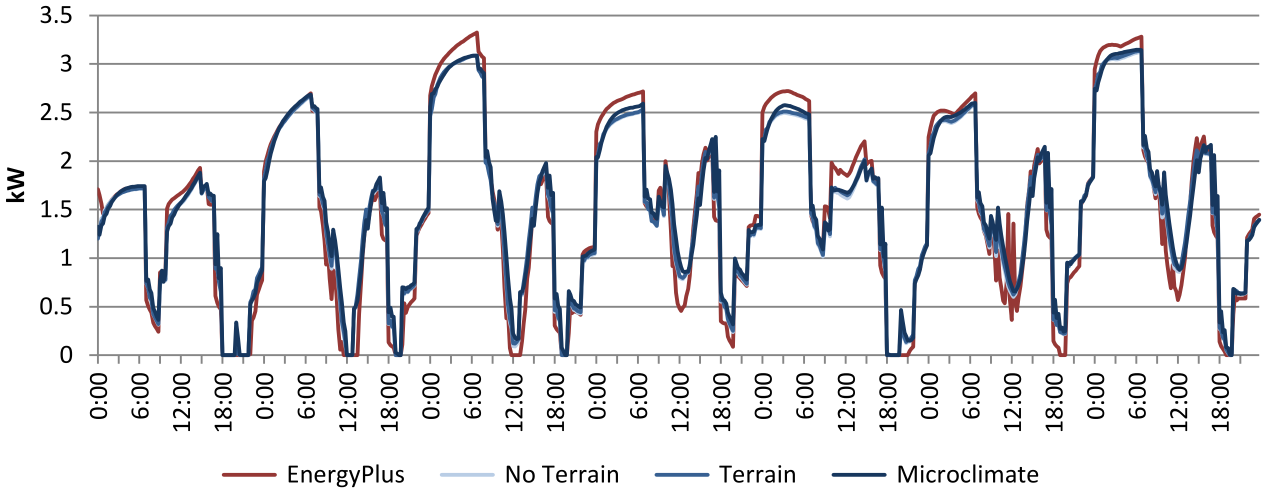
The winter design week, even though very slight, shows a pattern of increasing energy usage with each new component added. The statistical comparison with EnergyPlus in Table 9.1 shows a very good match for the *no terrain* and *terrain* scenes, even better than the final single building models during model development. The change in total energy demand between scenes is relatively small, with a difference of 2.7% between the *no terrain* stage, which had the most similar geometry, and the *microclimate* stage.

Table 9.1 – RadTherm rural scene winter design week heating compared with EnergyPlus

	Non-MC	No Terrain	Terrain	Microclimate
Total Energy Difference	0.92%	-0.17%	0.60%	2.56%
Correlation Coefficient	0.9892	0.9890	0.9885	0.9804
Normalized RMS Difference	5.63%	5.51%	5.57%	6.84%

A comparison of the heating curves, shown in Figure 9.1 below, is again similar to the development model comparison where the most significant deviations are at night during peak heating. There is also a significant difference during the middle of the fifth day, which is unlike any of the other days.

Figure 9.1 – Winter design week heating from EnergyPlus and RadTherm rural scenes



In Table 9.2 and Figure 9.2, the microclimate scenes in RadTherm are compared to the original single RadTherm building. This comparison shows that adding trees and adjusting the background surface conditions in the *no terrain* stage, has a very small effect on the heating demand. Adding a faceted terrain in the *terrain* stage and the microclimate air nodes in the *microclimate* stage also have small effects, with the air nodes being the most significant. The overall change is still relatively small, only 3% for the *microclimate* stage when compared to a standalone building.

Table 9.2 – RadTherm rural scene winter design week heating compared with single building

	No Terrain	Terrain	Microclimate
Total Energy Difference	0.32%	1.09%	3.07%
Correlation Coefficient	0.9998	0.9997	0.9953
Normalized RMS Difference	0.58%	0.91%	3.01%

The heater curves are all very similar, with the most significant differences during midday on the sunny days (days 3, 4, 6, 7) and at night for the latter half of the week. The midday differences can be explained by the increased absorption property of the terrain. The differences between the *microclimate* and *terrain* stages at night are interesting since there is very little difference between the air temperatures, which will be shown later.

Figure 9.2 – Winter design week heating from RadTherm rural scene and single building

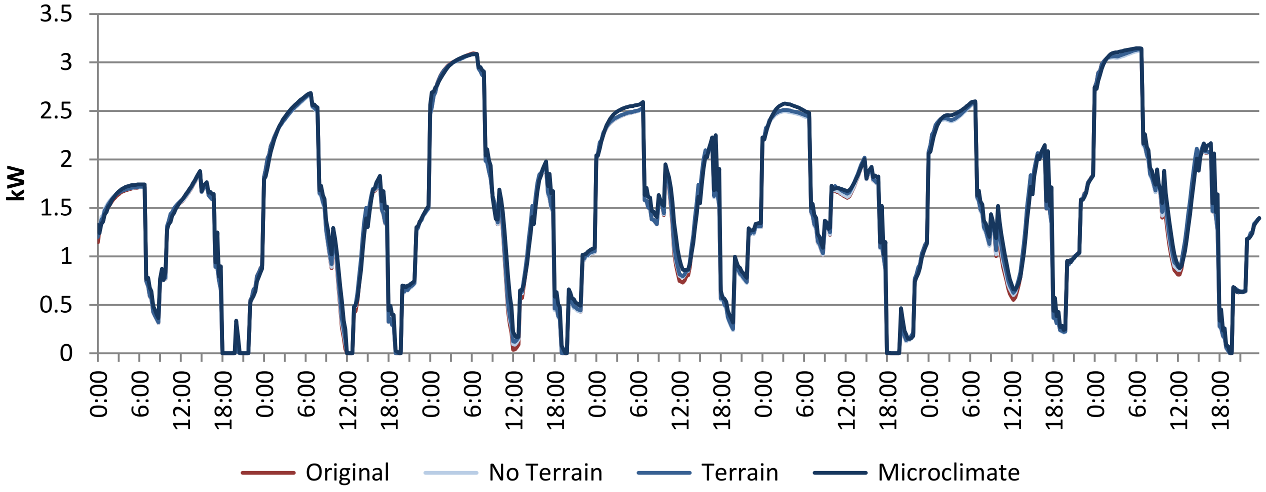
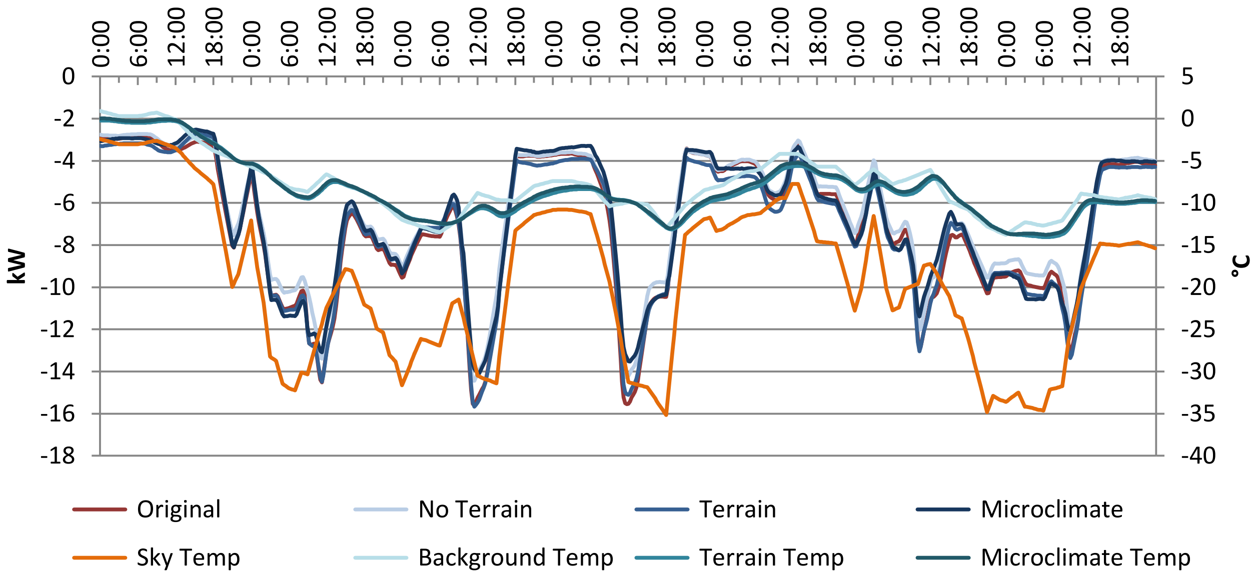


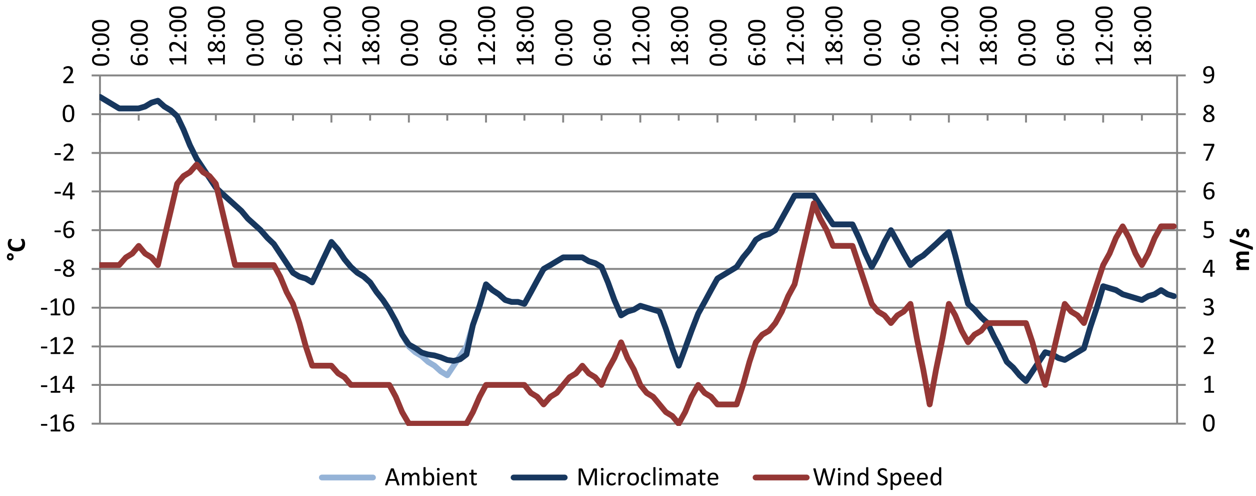
Figure 9.3 looks messy, but represents a lot information about the radiant nature of the winter microclimate. The top row of the legend identifies the curves for the radiant losses from the original RadTherm building and all scenes, and is graphed on the primary axis. The bottom row labels the temperature curves for sky and ground average, and is graphed on the secondary axis. The sky and ground are the two most significant objects affecting radiant gains, and are the only ones considered in EnergyPlus. Although the addition of a faceted terrain does have an effect on the radiant losses from the building, the values are small. The differences are caused by the faceted terrain usually having a lower surface temperature than the default background. However, it is clear by the correlation of the sky temperature curve with the radiant heat rate curves that the sky is the dominating environmental feature for radiation.

Figure 9.3 – Net radiation heat rate on vertical, exterior surfaces in the urban winter design week



At this point, there is no clear explanation for the differences between the *terrain* stage and the *microclimate* stage. The terrain temperatures are nearly identical, yet the radiant losses differ. Figure 9.4 below shows the ambient temperature compared with the local air temperature created by the microclimate air model. There are only a few hours during the third night where the temperatures deviate. The red curve is the met tower wind speed read in from the weather file, graphed on the secondary axis. It is possible that the wind convection in the microclimate model is behaving differently than the default wind method, and should be investigated further.

Figure 9.4 – Winter design week ambient and rural microclimate air temps with wind speed



Reviewing the wind speeds shows that the local air temperatures are very sensitive to air flow, and only when air flow is zero are they able to deviate by any significant amount. Interestingly, the timing of when the air flow stops is also the only time when the faceted terrain has a notably higher temperature than the default background.

9.1.2 Summer Design Week

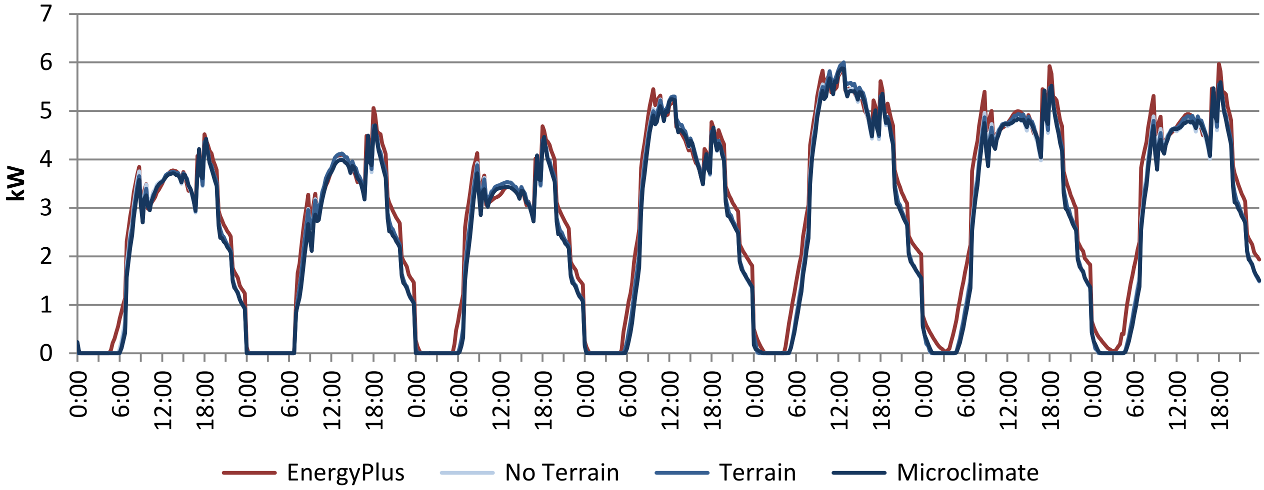
The summer design week shows that every microclimate stage has a lower energy demand than EnergyPlus, as shown in Table 9.3 below. The *terrain* stage has a small increase in demand over the *no terrain*, and the *microclimate* stage has the largest difference dropping 1.7% from the *terrain* scene.

Table 9.3 – RadTherm rural scene summer design week cooling compared with EnergyPlus

	Non-MC	No Terrain	Terrain	Microclimate
Total Energy Difference	-7.18%	-7.78%	-7.40%	-9.37%
Correlation Coefficient	0.9911	0.9914	0.9900	0.9876
Normalized RMS Difference	5.44%	5.59%	5.65%	6.72%

The chiller curves in Figure 9.5 show a good match during midday between the RadTherm and EnergyPlus models. However, in the mornings and evenings the RadTherm models have a lower demand, which is consistent with the single building model.

Figure 9.5 – Summer design week cooling from EnergyPlus and RadTherm rural scenes



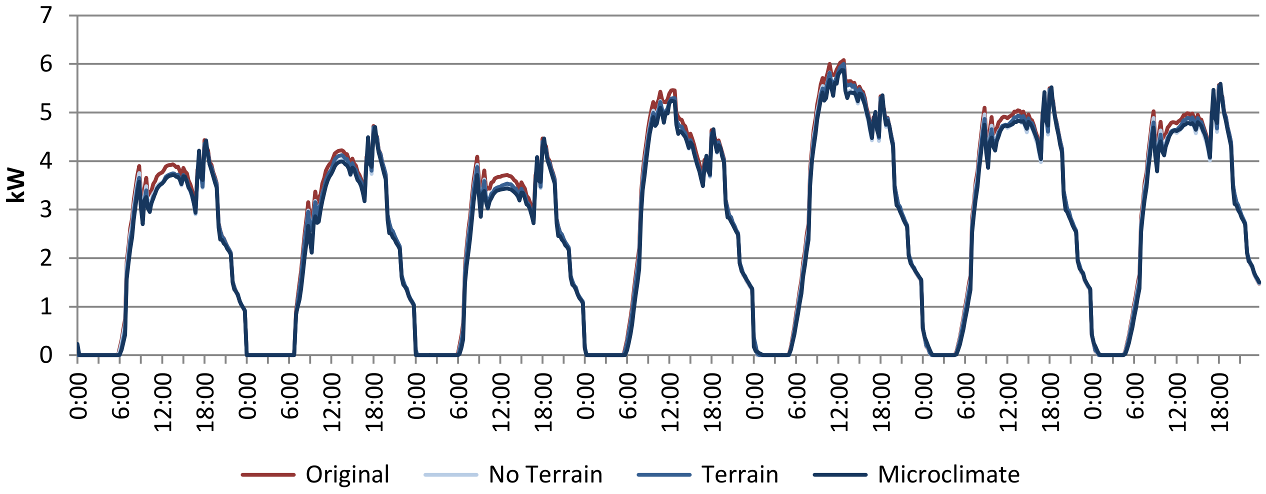
When compared to the single RadTherm building, the microclimate scenes show a more significant difference than during the winter week. In the *no terrain* stage, the difference is due to the background terrain surface properties since the trees are too far from the building to have a direct solar shading effect. Adding the faceted terrain increases demand only slightly, and then the *microclimate* stage reduces it again to the lowest levels. The full comparison of statistics is listed in Table 9.4 below.

Table 9.4 – RadTherm rural scene summer design week cooling compared with single building

	No Terrain	Terrain	Microclimate
Total Energy Difference	-3.22%	-2.82%	-4.89%
Correlation Coefficient	0.9997	0.9992	0.9974
Normalized RMS Difference	2.00%	1.96%	3.41%

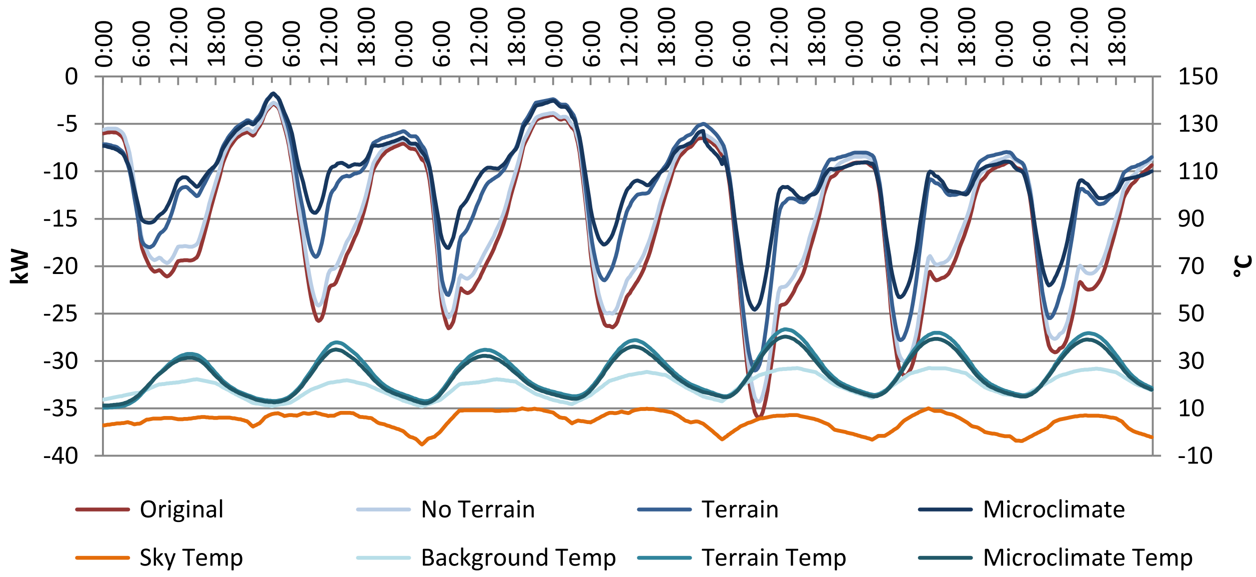
A review of the heater curves in Figure 9.6 show a somewhat opposite pattern from the EnergyPlus comparison, where the scene deviates from the control building regularly during the day and match very well during the mornings and evenings. It is difficult to see because the curves are so close, but the faceted terrain slightly increases demand during the afternoon hours. The microclimate air then reduces the demand predominantly in the morning hours between 08:00 and 12:00.

Figure 9.6 – Summer design week cooling from RadTherm rural scene and single building



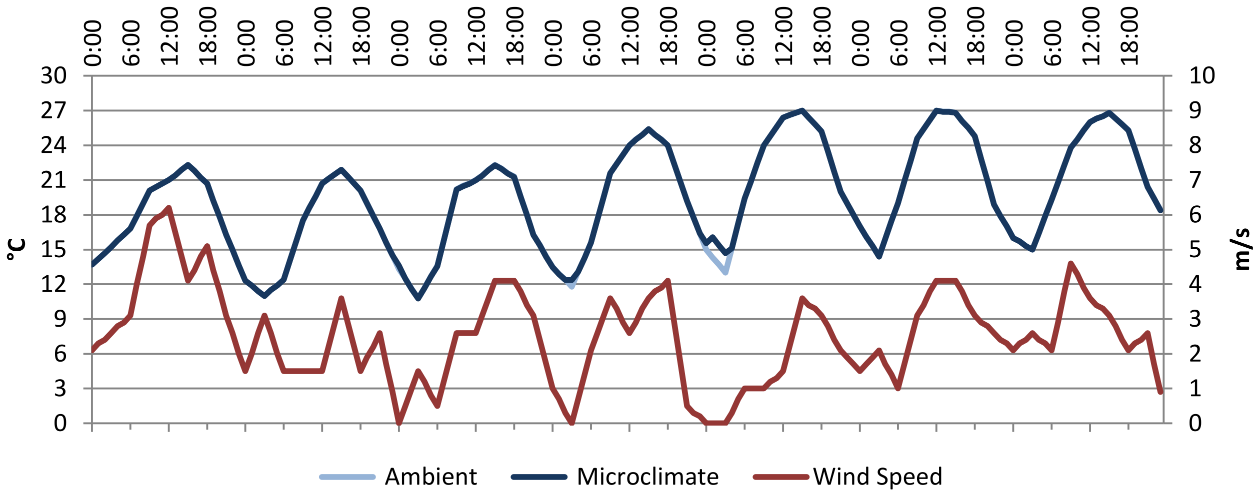
The differences in energy demand appear to be due to significant differences in radiant losses to the exterior of the building. Figure 9.7 below shows the net radiation heat rate of the exterior vertical surfaces. The control and *no terrain* buildings are similar, but the *terrain* and *microclimate* scenes show drastically lower radiant losses, an energy difference of 25% and 30% over the week, respectively. Shown on the same plot are the surface temperatures of the most significant objects in the scene, the terrain and sky. During midday, the faceted terrain can reach temperatures 20°C higher than the default background, which correlates to the changes in radiant heat rate. Unexpectedly, the microclimate scene has a notably different radiant heat rate, particularly during the morning hours when the cooling demand is reduced. The reduced cooling demand is opposite of what would normally be expected since the *microclimate* stage is losing less heat than the *terrain* stage.

Figure 9.7 – Net radiation heat rate on vertical, exterior surfaces in the urban summer design week



The microclimate air temperatures, plotted in Figure 9.8, do not offer much of an explanation for the energy differences either. Just as in the winter week, the local air temperatures only deviate from ambient when wind speeds are zero. This causes a short increase in local air temperature which should increase cooling demand; however demand is not significantly affected during these times. Once again, modified wind speeds could be to blame.

Figure 9.8 – Summer design week ambient and rural microclimate air temps with wind speed



9.1.3 Annual Simulations

The annual simulations produce a similar result pattern as is seen in each design week. The heating difference between EnergyPlus and RadTherm are still close to 6%, just as in the original single building models. The cooling loads are a few percentage points lower however, which may be in large part due to the adjusted terrain conditions.

Table 9.5 – Annual RadTherm rural scene results with EnergyPlus

	Non-MC	EnergyPlus	No Terrain	Terrain	Microclimate
Total Heating (kWh)	-	2842	3011	3039	3081
Difference	5.79%	-	5.90%	6.91%	8.37%
Total Cooling (kWh)	-	5739	5909	5922	5771
Difference	5.47%	-	2.97%	3.91%	0.57%
Correlation Coefficient	0.9859	-	0.9868	0.9859	0.9819
Normalized RMS Difference	2.91%	-	2.76%	2.85%	3.20%

In review of the rural scene with the original RadTherm model, the updating of the background to the correct surface condition has as much impact on the energy demand as the addition of the faceted terrain. As before, the *microclimate* stage had a slightly more noticeable effect. There are a number of times during the year when there is no air flow and the local air temperature deviates from ambient, but it does not seem like enough to cause the large difference in cooling. A more detailed review of the convection coefficients and wind speeds compared to the default wind model in the *terrain* stage will be necessary.

Table 9.6 – Annual RadTherm rural scene results with single building

	Single Building	No Terrain	Terrain	Microclimate
Total Heating (kWh)	2981	3011	3039	3081
Difference	-	0.98%	1.95%	3.34%
Total Cooling (kWh)	6161	5909	5922	5771
Difference	-	-4.09%	-3.88%	-6.32%
Correlation Coefficient	-	0.9997	0.9994	0.9978
Normalized RMS Difference	-	0.72%	0.79%	1.41%

The simulation times for EnergyPlus are surprisingly high in the rural case, and can be attributed to the surrounding tree geometry. The concave shapes and staggered orientation requires a considerable amount of solar reflection for diffuse lighting calculations. Unlike most of the simulations, the *no terrain* case is actually pretty close to EnergyPlus. However, the addition of a faceted terrain increases the computational costs considerably. The microclimate is also very expensive due to the necessary reduction in time step size for transitional periods from wind, to no wind, and back again.

Table 9.7 – Rural scene annual simulation solver run times

	EnergyPlus	No Terrain	Terrain	Microclimate
Run Time (s)	19,654	25,223	45,054	79,063
Run Time	5h 27m	7h 0m	12h 30m	21h 57m

9.2 Suburban

The results from the suburban scene are quite different in that the relative winter results are down several percentage points, and the summer up around 1%. During the winter week, there is a general trend towards increasing energy demand with each new component in a scale similar to the rural scene. In contrast, the summer week response to each terrain component, with the *terrain* stage requiring less energy than the other scenes. The annual simulations show increasing heating demand for each stage, but reduced cooling. The following sections review the results in detail.

9.2.1 Winter Design Week

The suburban winter design week statistics, shown in Table 9.8 below, are notably different from the rural scene. The total energy demand increases with each new component added, however all stages are lower than the single building case. Since the terrain was still set to grass in the *no terrain* stage, this indicates a difference between shading from the trees. The change in total energy demand between scenes is more in this case, but still relatively small, with a total difference of approximately 2.48% between the *no terrain* stage and the *microclimate* stage.

Table 9.8 – RadTherm suburban scene winter design week heating compared with EnergyPlus

	Non-MC	No Terrain	Terrain	Microclimate
Total Energy Difference	0.92%	-4.90%	-4.18%	-2.55%
Correlation Coefficient	0.9892	0.9860	0.9928	0.9756
Normalized RMS Difference	5.63%	6.04%	4.62%	6.96%

A comparison of the heating curves with EnergyPlus is shown in Figure 9.9 below. Once again the most significant deviations are at night during peak heating, as well as the middle of the fifth day, which is unlike any of the other days.

Figure 9.9 – Winter design week heating from EnergyPlus and RadTherm suburban scenes

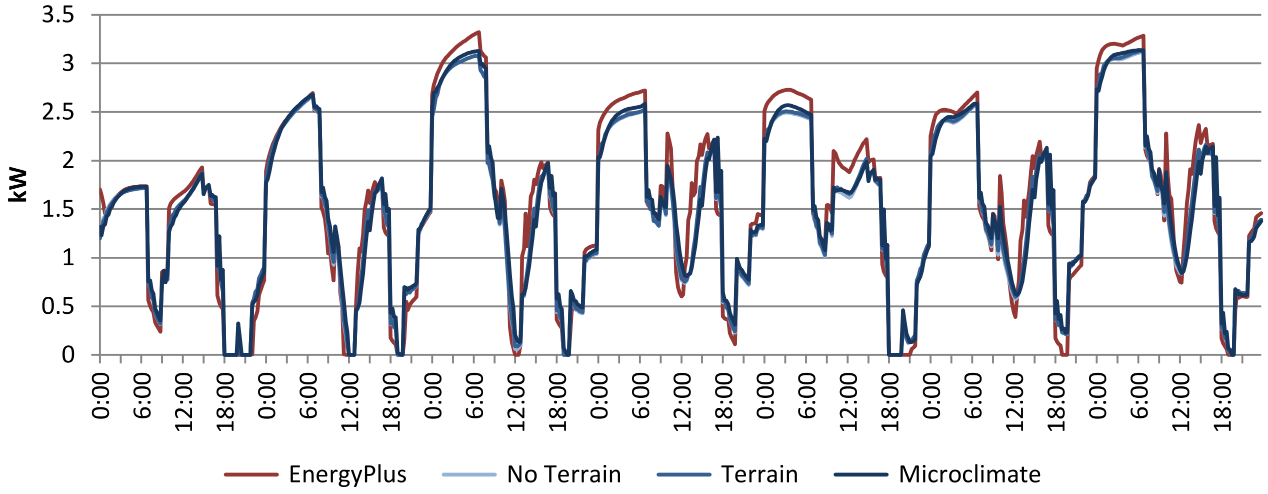


Table 9.9 has the statistical comparison to the original single RadTherm buildings, showing that the total energy demand increases with each stage. The revised terrain surfaces and addition of buildings and trees in the *no terrain* stage makes effectively no difference, while the jump between the terrain and microclimate stages is the most significant at 1.73%. Ultimately, these differences are very small relative to the uncertainty currently present in BES models.

Table 9.9 – RadTherm suburban scene winter design week heating compared with single building

	No Terrain	Terrain	Microclimate
Total Energy Difference	0.06%	0.81%	2.54%
Correlation Coefficient	0.9998	0.9996	0.9951
Normalized RMS Difference	0.55%	0.85%	2.95%

As indicated by the very high correlations and low NRMS values above, the heater curves in Figure 9.10 below are nearly identical. The microclimate curve shows some deviation during the fourth and fifth nights, but the rest of the time the scenes have no significant difference.

Figure 9.10 – Winter design week heating from RadTherm suburban scene and single building

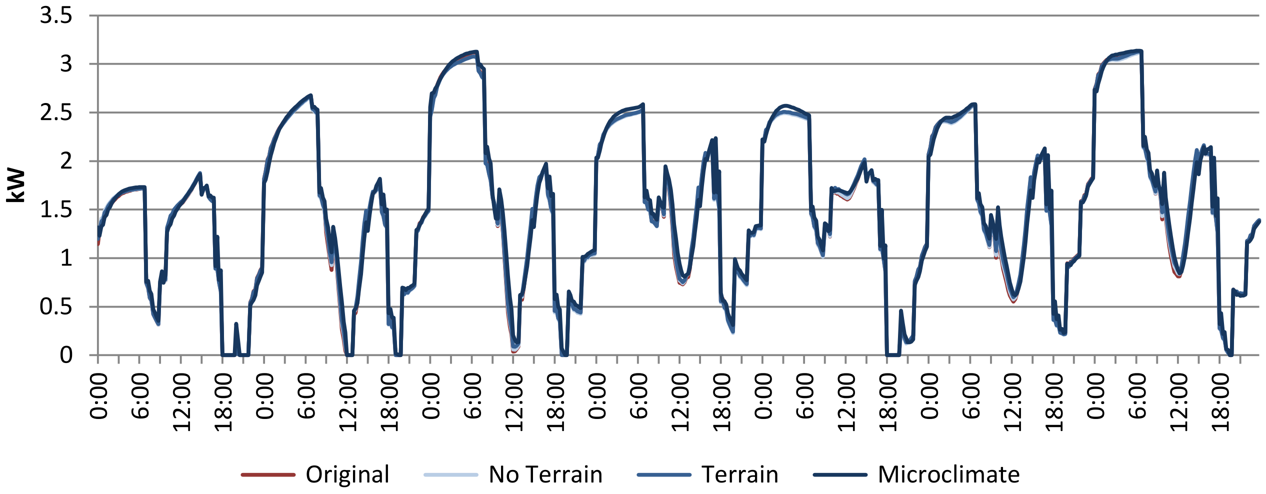


Figure 9.11 is a plot of the radiant heat rate of the vertical, exterior surfaces of the target building overlaid with the surface temperatures of the most significant sources of radiant interaction in the environment; the sky and various terrains. Just as in the rural scene, the heat rates are very similar between scenes and the sky dominates the radiant exchange.

Figure 9.11 – Net radiation heat rate on vertical, exterior surfaces in the urban winter design week

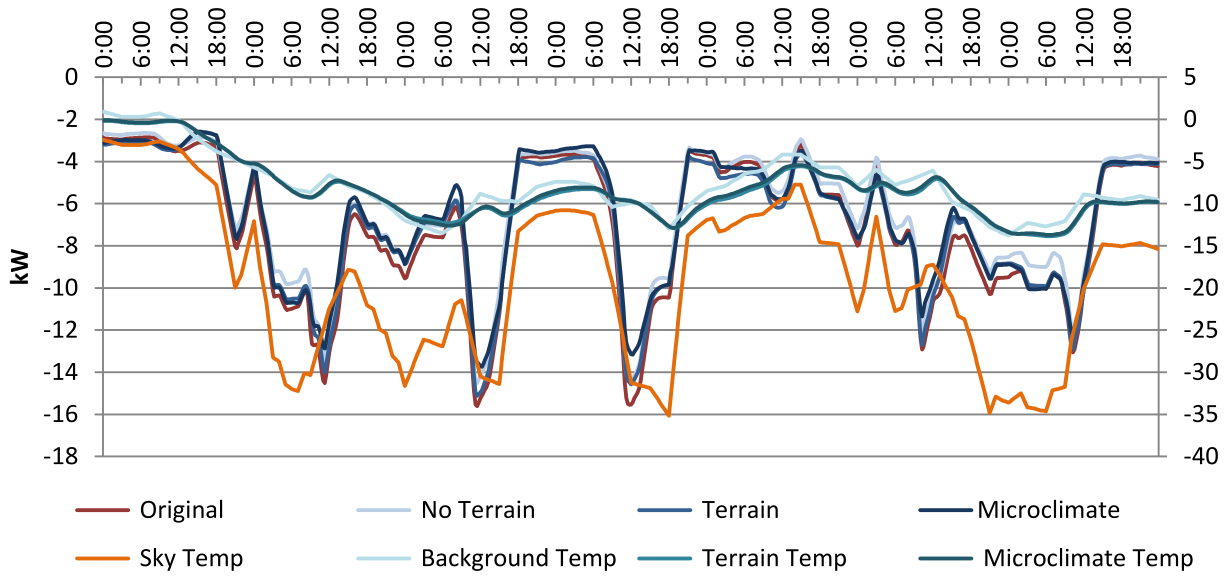
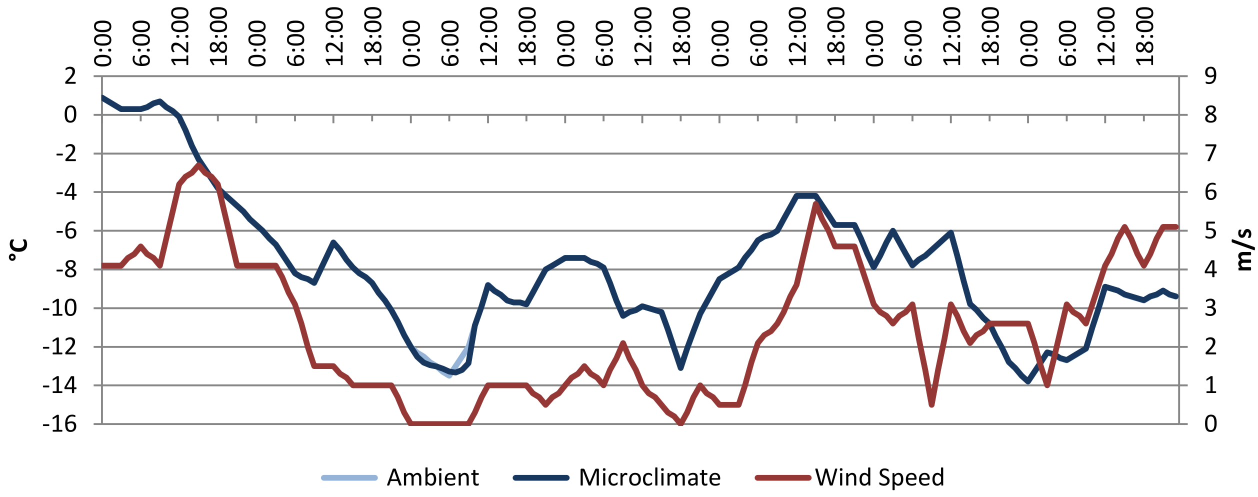


Figure 9.12 is a review of the effect of the microclimate air model. Just as in the rural scene, the local air node only deviates from ambient air when there is no wind flow. There is a slight difference in the microclimate air temperature, but it never deviates more than 0.5°C from ambient.

Figure 9.12 – Winter design week ambient and suburban microclimate air temps with wind speed



9.2.2 Summer Design Week

The suburban summer design results show slightly more cooling demand from RadTherm, but very little difference between the stages. The comparison to the EnergyPlus simulation in Table 9.10 shows that the stages have less than a 0.40% difference between them, with the *terrain* stage demanding the most energy. This is a considerably smaller difference than the rural scene, and effectively insignificant.

Table 9.10 – RadTherm suburban scene summer design week cooling compared with EnergyPlus

	Non-MC	No Terrain	Terrain	Microclimate
Total Energy Difference	-7.18%	-6.06%	-6.43%	-6.29%
Correlation Coefficient	0.9911	0.9908	0.9897	0.9879
Normalized RMS Difference	5.44%	5.17%	5.41%	5.78%

The heater curves plotted in Figure 9.13 show a good correlation during most days, with the most significant deviations occurring in the evenings and for a short period during the third day.

Figure 9.13 – Summer design week cooling from EnergyPlus and RadTherm suburban scenes

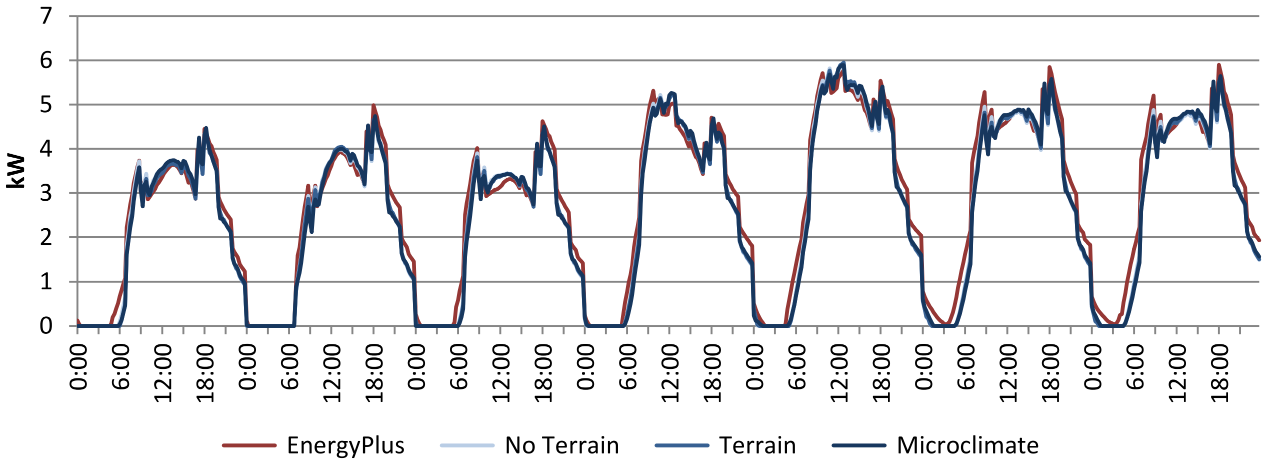


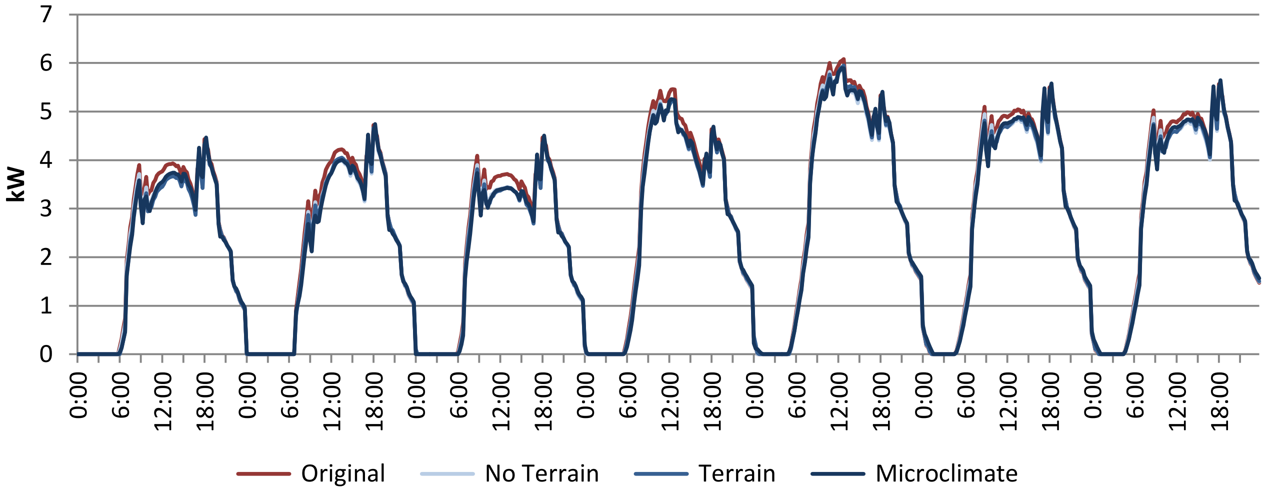
Table 9.11 below lists the statistical comparison between the suburban scene and the original RadTherm single building. The scene does have a notable effect on the energy demand, with the *terrain* stage requiring nearly 4% less cooling energy. The other stages only require a marginal amount of additional cooling.

Table 9.11 – RadTherm suburban scene summer design week cooling compared with single building

	No Terrain	Terrain	Microclimate
Total Energy Difference	-3.60%	-3.98%	-3.83%
Correlation Coefficient	0.9995	0.9987	0.9972
Normalized RMS Difference	2.28%	2.66%	3.13%

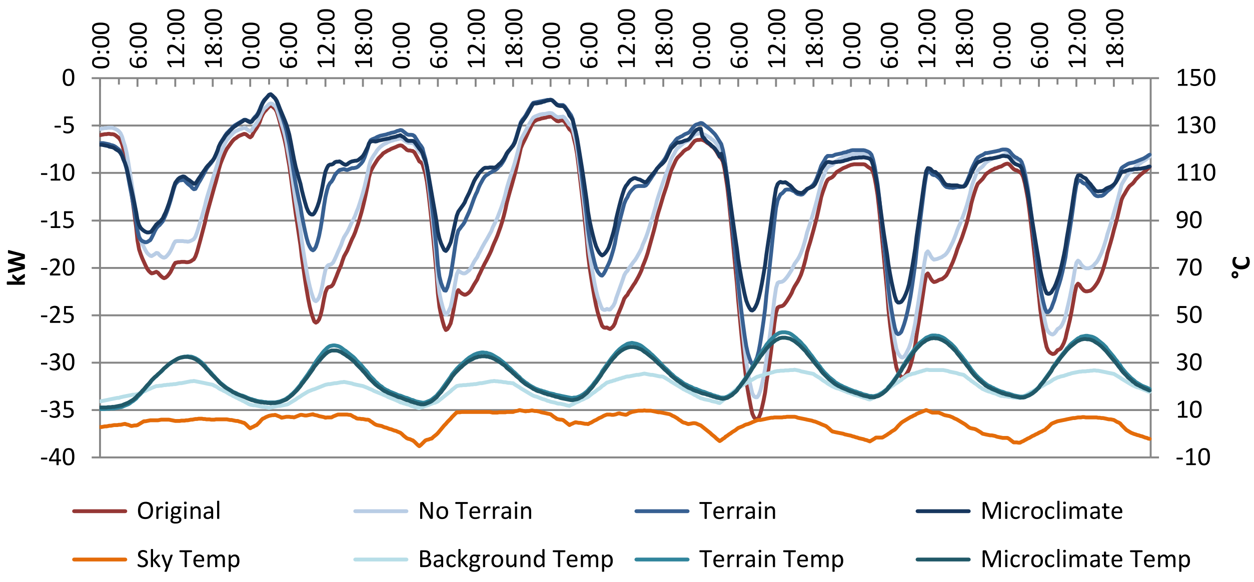
The cooling power curves in Figure 9.14 show a similar pattern to the rural scene, where the greatest deviations are during the day and the scene requires less power than the single building. Given the rural scene's results, it is safe to assume that the bulk of the difference is due to the terrain surface properties versus the shading from trees.

Figure 9.14 – Summer design week cooling from RadTherm suburban scene and single building



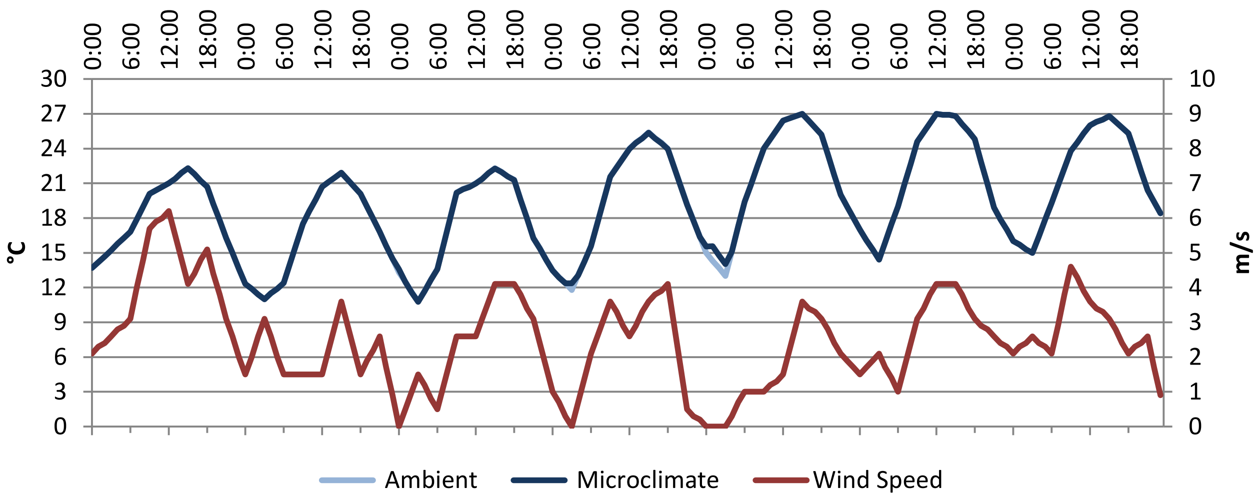
The radiant heat rates for all of the suburban RadTherm models compared with the single building are reported in Figure 9.15 below. Just as in the rural case, there is a minor change when the objects are added and background updated in the *no terrain* stage and a much more significant change in the *terrain* stage when the terrain is able to increase in temperature from ambient. Unexpectedly, the *microclimate* stage has noticeably less radiant losses than the *terrain* stage; however the difference is less than the rural case. The terrain temperatures shown are an area weighted average of the grass and road, and are typically 1°C higher than the grass only terrain during midday.

Figure 9.15 – Net radiation heat rate on vertical, exterior surfaces in the urban summer design week



The microclimate air temperatures in Figure 9.16 show very little separation from the ambient air temperatures, with only a 0.5°C difference during the slowest wind period.

Figure 9.16 – Summer design week ambient and suburban microclimate air temps with wind speed



9.2.3 Annual Simulations

The annual simulations for the suburban scene are interesting when compared to EnergyPlus. The heating loads are relatively much lower than in the single building case, however the cooling load difference is similar. The difference between stages is once again rather small, less than 2%. A complete listing of results is in Table 9.12 below.

Table 9.12 – Annual RadTherm suburban scene results with EnergyPlus

	Non-MC	EnergyPlus	No Terrain	Terrain	Microclimate
Total Heating (kWh)	-	2991	3010	3044	3078
Difference	5.79%	-	0.64%	1.77%	2.92%
Total Cooling (kWh)	-	5569	5840	5797	5720
Difference	5.47%	-	4.87%	4.11%	2.72%
Correlation Coefficient	0.9859	-	0.9864	0.9859	0.9832
Normalized RMS Difference	2.91%	-	2.81%	2.83%	3.07%

When compared to the original RadTherm model, the results in Table 9.13 are quite different. The heating differences actually compare very similarly to EnergyPlus; however cooling is significantly less and decreases with each stage. Given the close correlation in EnergyPlus and the significant decrease in cooling in the RadTherm model, the change in cooling is likely due to shading from the trees close to the building more than other climatic effects.

Table 9.13 – Annual RadTherm suburban scene results with single building

	Single Building	No Terrain	Terrain	Microclimate
Total Heating (kWh)	2981	3010	3044	3078
Difference	-	0.96%	2.09%	3.25%
Total Cooling (kWh)	6161	5840	5797	5720
Difference	-	-5.21%	-5.90%	-7.15%
Correlation Coefficient	-	0.9994	0.9989	0.9976
Normalized RMS Difference	-	0.93%	1.11%	1.53%

The simulation time for EnergyPlus is once again notably high due to the trees. RadTherm times for the *no terrain* stage are reasonably close, but the *terrain* and *microclimate* stages are again considerably longer.

Table 9.14 – Suburban roof scene annual simulation solver run times

	EnergyPlus	No Terrain	Terrain	Microclimate
Run Time (s)	18,254	25,448	49,321	80,904
Run Time	5h 4m	7h 4m	13h 42m	22h 28m

9.3 Urban

The urban simulations show the most dramatic results of all the scenes; however they are not as expected. The winter cases once again show increasing heating demand with each microclimate stage, but relative values that are generally less than EnergyPlus. The summer week scenes are unusual in that they actually show the greatest reduction in energy demand of all the scenes, completely going against the notion of capturing the heat island effect. The annual simulations confirm both of these results. The following sections review the results in detail.

9.3.1 Winter Design Week

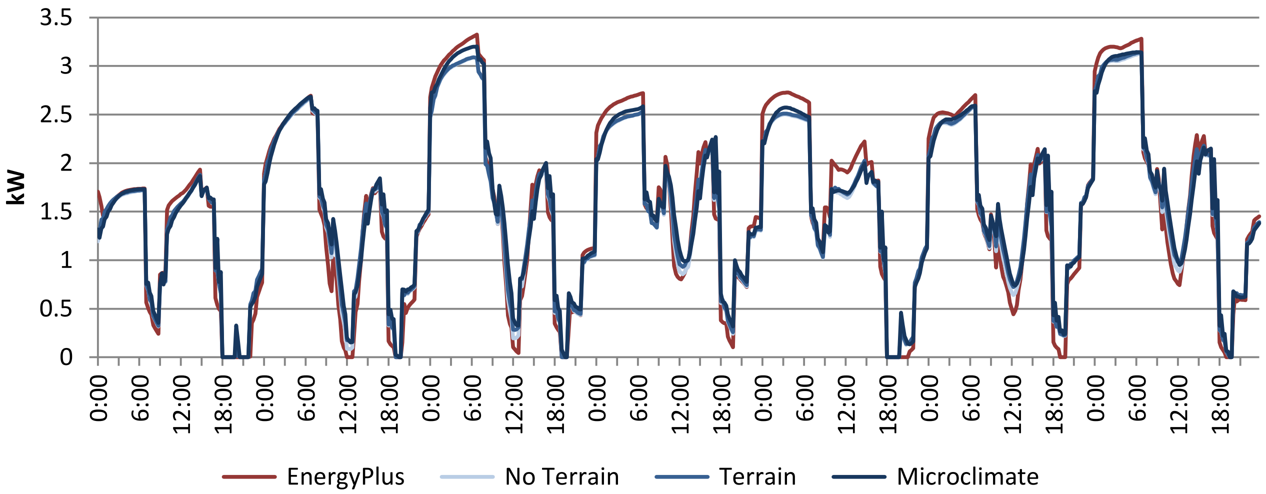
As mentioned above, the winter design week scenes follow the same pattern of increased heating demand with the addition of each component. In comparison with EnergyPlus, the total energy demand of the *terrain* stage is nearly the same, with the *no terrain* stage requiring 1.58% less heating and the *microclimate* stage requiring 1.38% more. The full listing of statistics is reported in Table 9.15 below, with a reference to the differences in the non-microclimate simulations from the BES development for comparison.

Table 9.15 – RadTherm urban scene winter design week heating compared with EnergyPlus

	Non-MC	No Terrain	Terrain	Microclimate
Total Energy Difference	0.92%	-1.58%	-0.32%	1.38%
Correlation Coefficient	0.9892	0.9923	0.9914	0.9825
Normalized RMS Difference	5.63%	4.78%	4.93%	6.09%

The heater curves in Figure 9.17 show the greatest deviations from EnergyPlus during peak heating at night, low heating situations during the day and periods of high internal gain. This has been a common pattern of all RadTherm models when compared to EnergyPlus, and the urban scenes are simply translated upward a few hundred watts relative to the other environments.

Figure 9.17 – Winter design week heating from EnergyPlus and RadTherm urban scenes



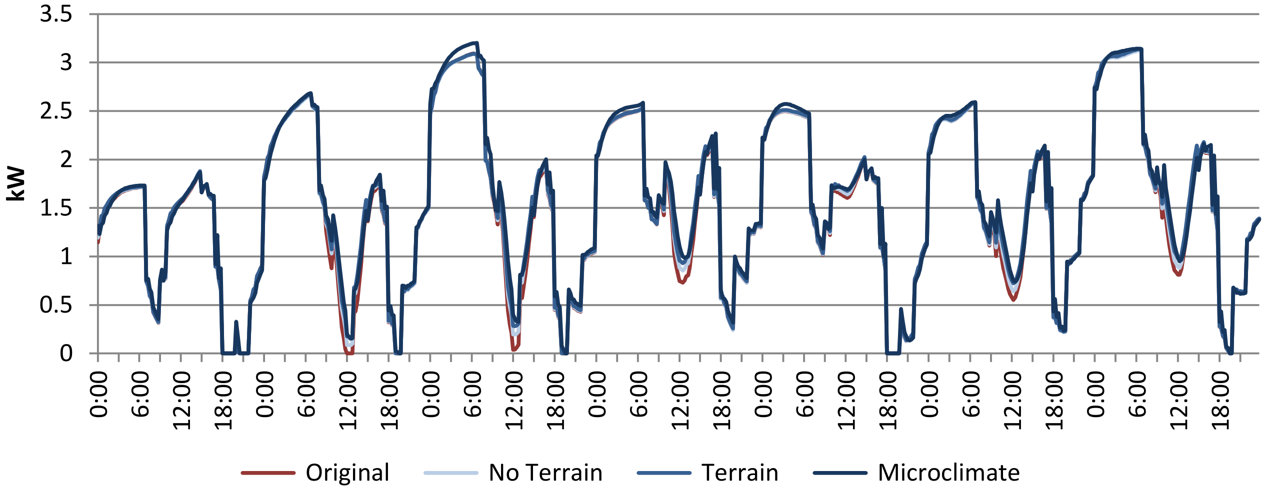
When compared to the original RadTherm single building, the results are more interesting. Table 9.16 shows that each stage has nearly the same effect on demand, and the *microclimate* stage has the largest difference in heating demand of any weekly simulation at 4.5%. It is worth pointing out however that the asphalt terrain has a significantly higher absorption level than the default used in the single building models.

Table 9.16 – RadTherm urban scene winter design week heating compared with single building

	No Terrain	Terrain	Microclimate
Total Energy Difference	1.43%	2.72%	4.48%
Correlation Coefficient	0.9987	0.9972	0.9927
Normalized RMS Difference	1.59%	2.46%	3.85%

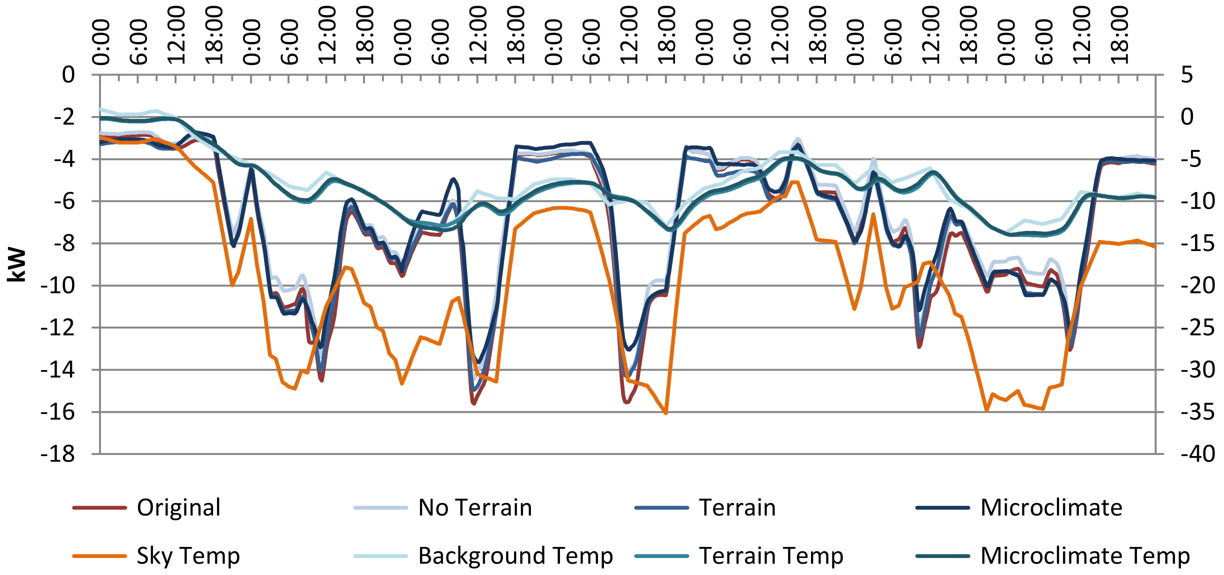
In Figure 9.18, the heater curves from the RadTherm models show the most significant deviations from the single building during sunny days, which correlates with the changed terrain properties. Additionally, the *microclimate* stage has the greatest difference from the terrain scene during the third night, with additional discrepancies during the fourth and fifth nights. Midday differences are predominantly due to shading from the close buildings.

Figure 9.18 – Winter design week heating from RadTherm urban scene and single building



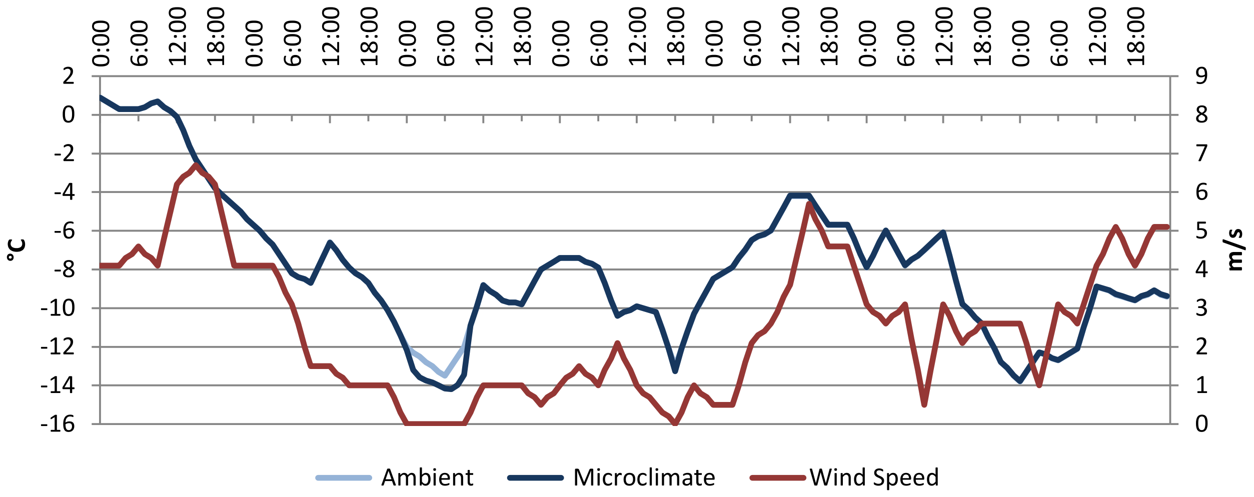
One possibility for the nighttime differences is increased radiant heat loss, however as Figure 9.19 shows, the *microclimate* stage has the least amount of radiant heat loss during those periods. As in all of the other winter simulations, the sky remains the most dominant source of radiant heat loss.

Figure 9.19 – Net radiation heat rate on vertical, exterior surfaces in the urban winter design week



Looking at Figure 9.20, the microclimate air temperature is significantly lower during the no wind speed hours on the third night, up to 2°C. This difference could be enough to cause the increase in heater demand between the *microclimate* and *terrain* stages. However the lack of a temperature difference during the other nights conflicts this explanation.

Figure 9.20 – Winter design week ambient and urban microclimate air temps with wind speed



9.3.2 Summer Design Week

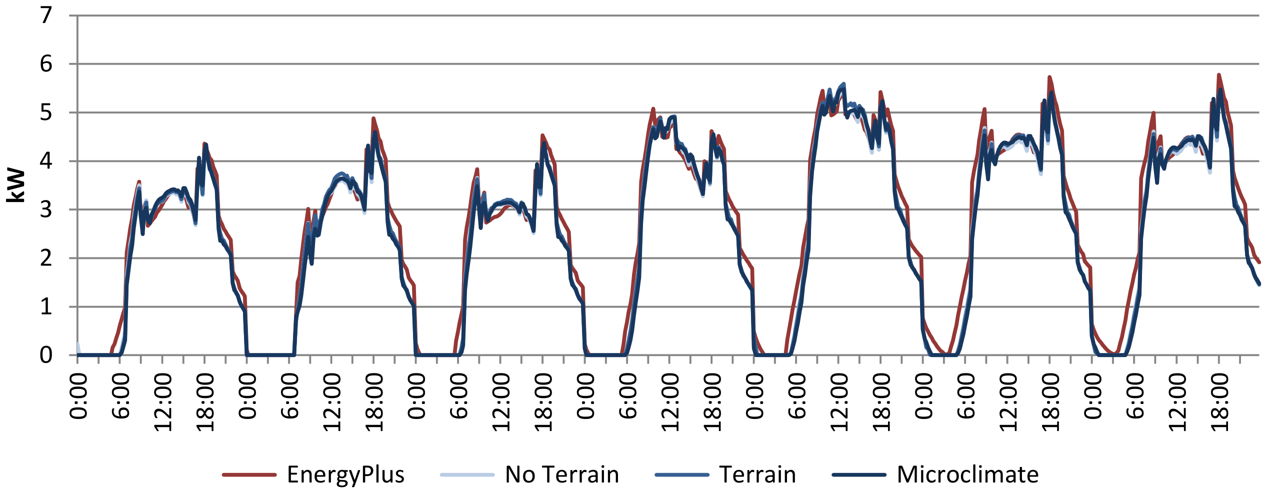
The urban summer design week has some of the most interesting results in the study. Of particular interest to researchers is modeling the urban heat island effect, an event that increases energy demand for cooling. However, all of the RadTherm urban stages demand less cooling than both EnergyPlus and the single building. Table 9.17 shown below, lists all of the statistics from the EnergyPlus comparison, with a reference to the differences in the non-microclimate simulations from the BES development. The differences in the microclimate cases are similar to the differences in the single building case, indicating that the simulations are still working in the same way and there are no new conditions to separate them. Similar to the rural case, the cooling demand increases with the addition of the faceted terrain, then decreases significantly with the inclusion of the microclimate air model.

Table 9.17 – RadTherm urban scene summer design week cooling compared with EnergyPlus

	Non-MC	No Terrain	Terrain	Microclimate
Total Energy Difference	-7.18%	-7.76%	-6.98%	-8.28%
Correlation Coefficient	0.9911	0.9903	0.9882	0.9855
Normalized RMS Difference	5.44%	5.86%	5.89%	6.80%

As with most comparisons with EnergyPlus, the RadTherm scenes match well during daytime hours and deviate the most during transitional morning and evening times. The EnergyPlus and RadTherm scene curves are plotted in Figure 9.21 below.

Figure 9.21 – Summer design week cooling from EnergyPlus and RadTherm urban scenes



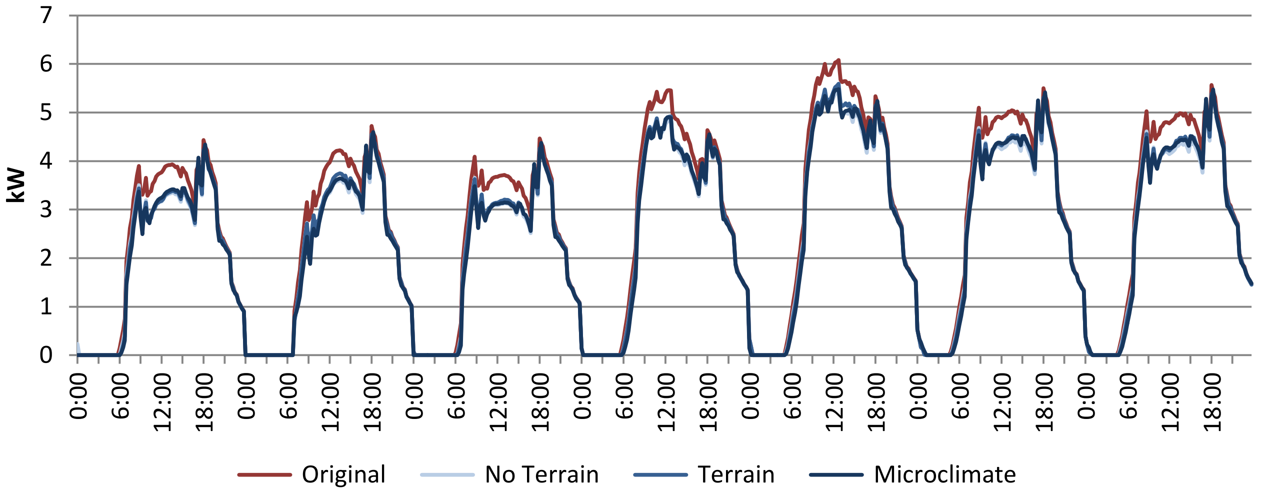
When compared to the original RadTherm model, the microclimate stages show a significant deviation. The *no terrain* scene reduces cooling demand by 9.37% which is due to the reduced solar load from building shading and increased absorption in the asphalt terrain. The faceted terrain increases demand a small amount, and then the microclimate air model reduces it again to nearly 10% below the original scene. All statistics for the comparison are in Table 9.18 below.

Table 9.18 – RadTherm urban scene summer design week cooling compared with single building

	No Terrain	Terrain	Microclimate
Total Energy Difference	-9.37%	-8.61%	-9.88%
Correlation Coefficient	0.9969	0.9968	0.9946
Normalized RMS Difference	6.31%	5.61%	6.65%

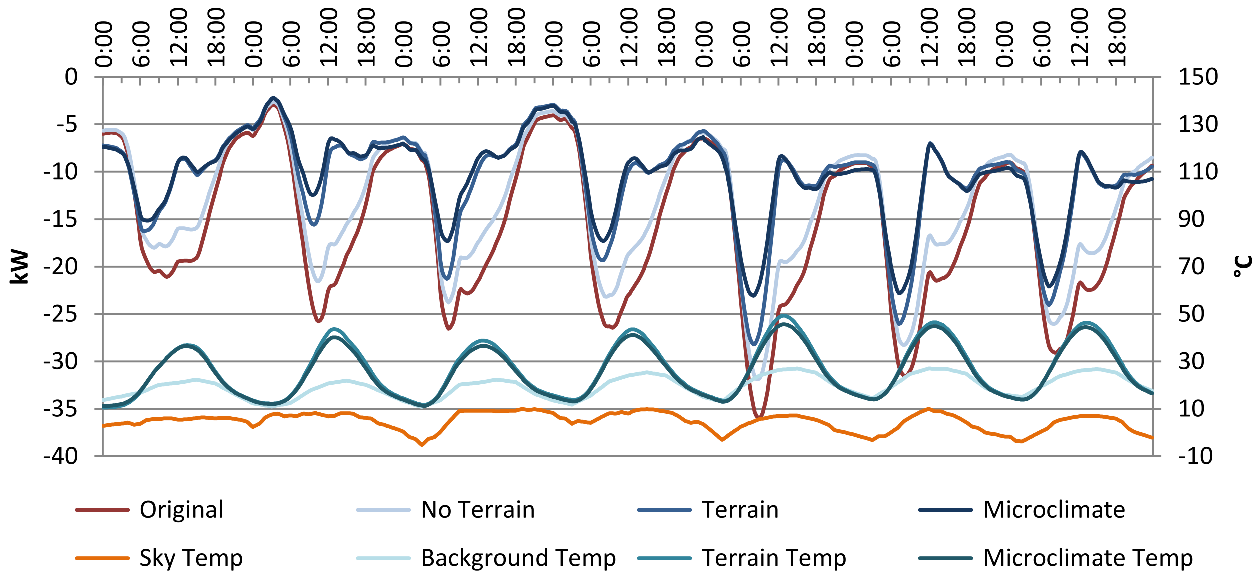
Figure 9.22 shows the cooling demand curves from each urban RadTherm simulation for the summer design week. The stage curves have a much lower demand during the daytime, when the solar differences are most prominent. There is small difference between *terrain* and *microclimate* stages on the second day, and for a very short period on the fifth day, but otherwise all of the RadTherm curves are well aligned.

Figure 9.22 – Summer design week cooling from RadTherm urban scene and single building



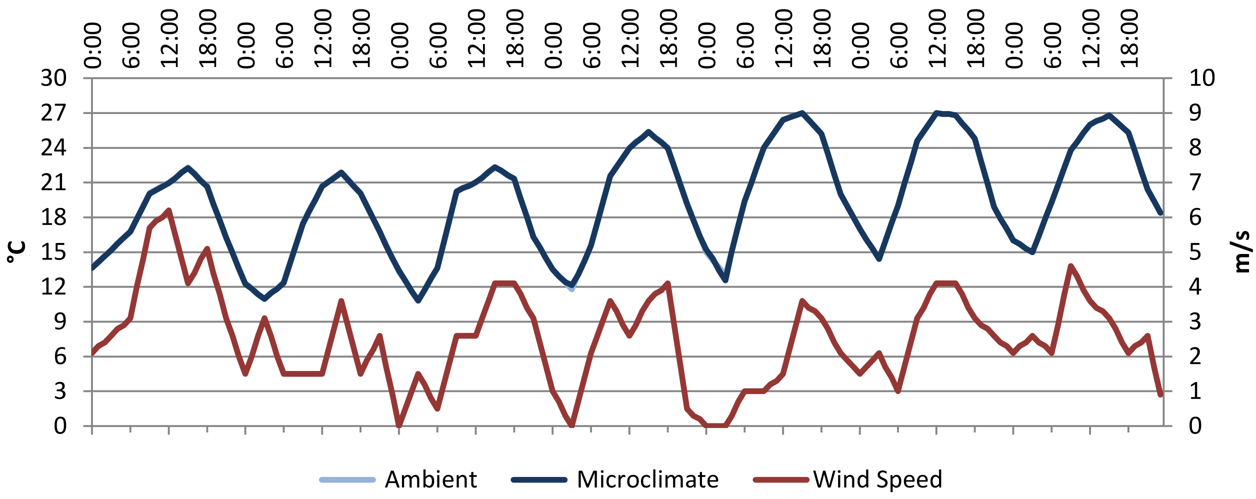
The radiation curves shown in Figure 9.23 clearly show the reduced radiant losses due to the revised terrain surface and additional buildings in the *no terrain* stage, but more so with the addition of a faceted terrain in the *terrain* stage. Interestingly, the difference between the *terrain* and *microclimate* stage heat rate is less here than in other environments.

Figure 9.23 – Net radiation heat rate on vertical, exterior surfaces in the urban summer design week



Another interesting result is the lack of any significant difference in the ambient and microclimate air temperatures, shown in Figure 9.24 below. While the differences were small in other scenes, the increased temperature and surface area of brick and asphalt present in the urban scene is expected to increase the convective gains to the local air, and thus the temperature.

Figure 9.24 – Summer design week ambient and urban microclimate air temps with wind speed



9.3.3 Annual Simulations

The annual simulation results mimic the patterns seen in the design weeks, with heating demand consistently increasing, and fluctuations in cooling through the stages. Table 9.19 reports the comparison results with EnergyPlus, including the original single building comparison. The *no terrain* and *terrain* stages have similar heating differences as the original building, and the microclimate stage sees a marked increase. Cooling demand in all scenes is down significantly, which is very surprising given the increase in radiant loading in RadTherm.

Table 9.19 – Annual RadTherm urban scene results with EnergyPlus

	Non-MC	EnergyPlus	No Terrain	Terrain	Microclimate
Total Heating (kWh)	-	2950	3103	3130	3191
Difference	5.79%	-	5.18%	6.11%	8.17%
Total Cooling (kWh)	-	5517	5458	5490	5357
Difference	5.47%	-	-1.06%	-0.47%	-2.89%
Correlation Coefficient	0.9859	-	0.9882	0.9870	0.9838
Normalized RMS Difference	2.91%	-	2.63%	2.74%	3.05%

When compared to the original RadTherm model, shown in Table 9.20, the results are extremely surprising. Of the three scenes, the urban case has the greatest increase in heating demand, as well as the greatest decrease in cooling. The increase in heating is most likely due to the decrease in solar gains during winter from shading. The large increase in the *microclimate* stage is also interesting since there are only a handful of periods when the local air temperature deviates from the ambient. There is a considerable decline in cooling demand, which may be due to shading but could also be the increased absorption of the asphalt. The addition of surrounding buildings reduced total solar gains for the year by almost 1000 kWh.

Table 9.20 – Annual RadTherm urban scene results with single building

	Single Building	No Terrain	Terrain	Microclimate
Total Heating (kWh)	2981	3103	3130	3191
Difference	-	4.07%	5.00%	7.03%
Total Cooling (kWh)	6161	5458	5490	5357
Difference	-	-11.41%	-10.89%	-13.05%
Correlation Coefficient	-	0.9969	0.9967	0.9949
Normalized RMS Difference	-	2.16%	2.08%	2.52%

Table 9.21 lists the run times for each simulation. Without the concave tree geometry, each stage runs notably faster, particularly EnergyPlus and the *microclimate* stage. Interestingly, in other scenes, EnergyPlus did not have as large of an advantage, whereas here the time gap makes a significant difference to how the running of simulations may be approached.

Table 9.21 – Urban scene annual simulation solver run times

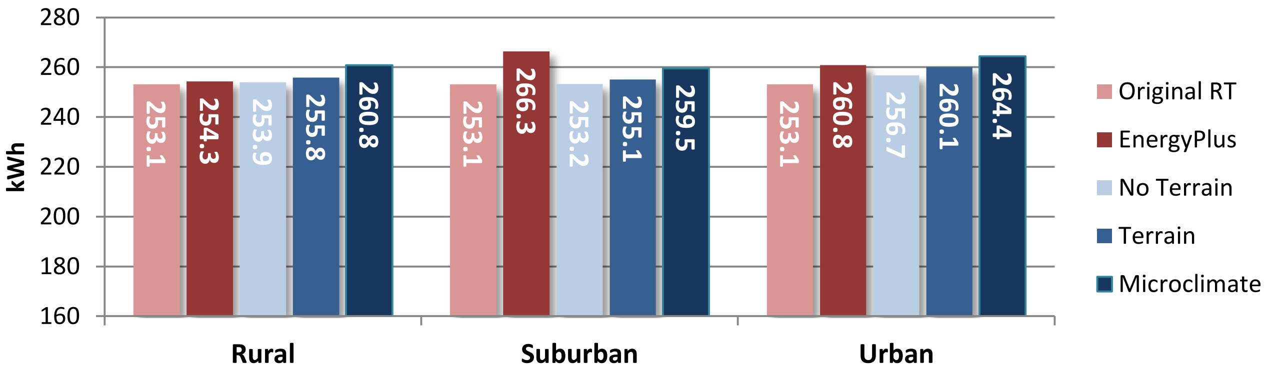
	EnergyPlus	No Terrain	Terrain	Microclimate
Run Time (s)	634	22,146	46,054	58,474
Run Time	0h 10m	6h 9m	12h 47m	16h 14m

9.4 Summary

There a considerable amount of information presented in the microclimate modeling results, most of which is rather dispersed amongst the previous 20 pages. This section is intended to provide a brief summary of the results to make the information more accessible. There are short descriptions of the model's behaviors, comments on reasons for the results, as well as all tables of the energy demand totals.

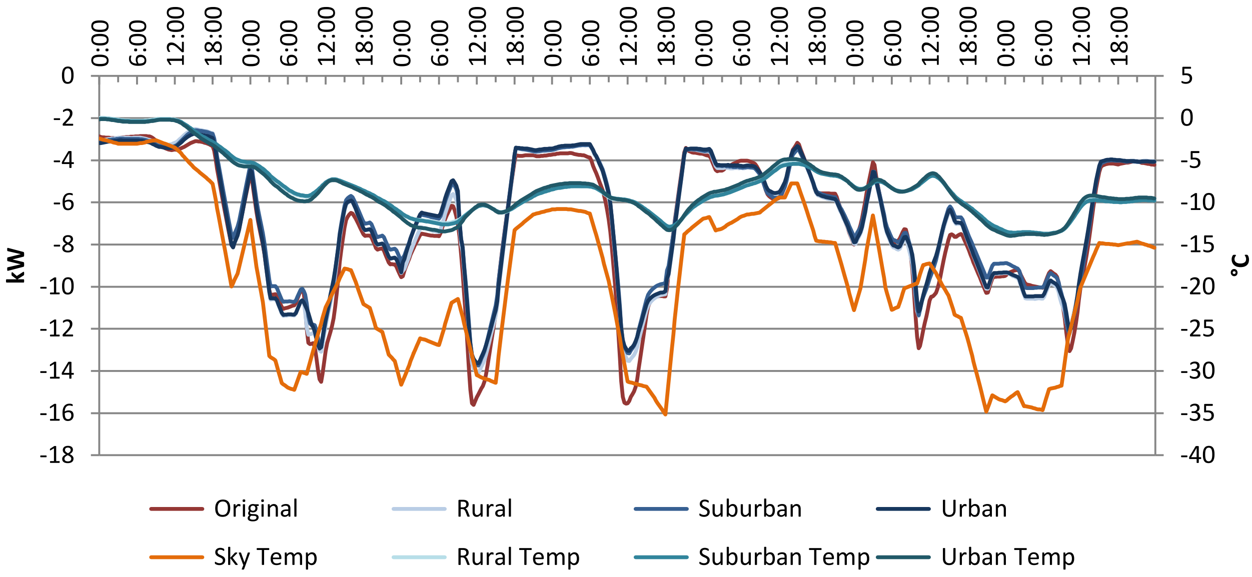
In most of the simulations, the differences between the three stages of microclimate modeling are relatively minor, usually resulting in a total energy difference of a few percent. The winter design week take the background surface properties out of the equation with every scene and stage being set with a snowy surface. Interestingly, the faceted terrain and microclimate air each cause an increase in heating demand equivalent to the summer week scale. This is a surprise given that the faceted and default terrains were rarely more than 1°C different, and the net radiant losses in each stage have insignificant differences. Total heating demand results are listed in Figure 9.25 below.

Figure 9.25 – Winter design week heating totals



While the energy demand response from within the buildings does not react as dramatically as expected, the radiant heat transfer occurring outside the building appears to be occurring correctly. With the winter scene having such cold ambient temperatures and little solar radiation, the radiation exchange is largely dominated by the sky temperatures and the radiant heat loss rates are very similar from stage to stage. Radiant heat losses and terrain temperatures for the *microclimate* stage during the winter week can be seen in Figure 9.26 below.

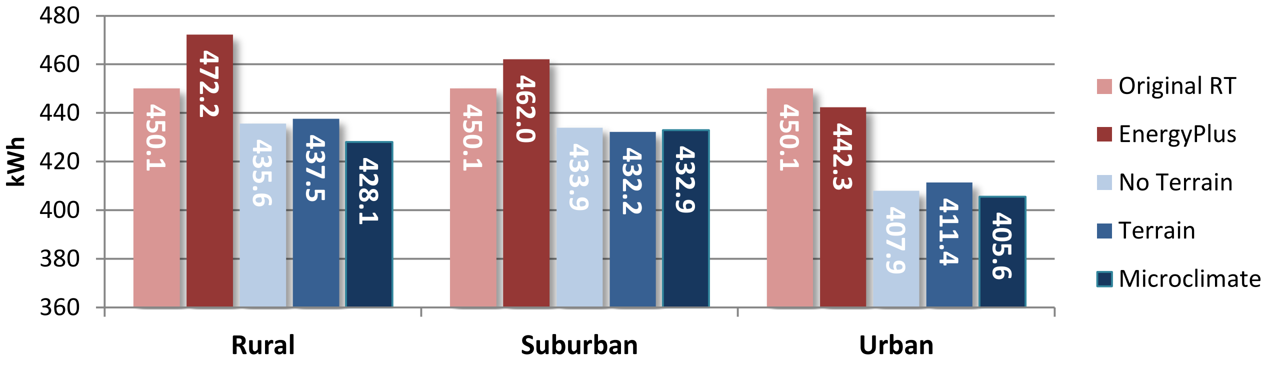
Figure 9.26 – Radiant heat loss and terrain temperature comparison between winter MC scenes



The elevated terrain and building temperatures fail to cause any significant elevation in local air temperatures. When the air temperatures are plotted against the wind speed, it becomes very clear that the ability to build up heat in the air is very sensitive to wind speed. Only when the wind stops does the air temperature have a chance to be altered.

In the summer design week results in Figure 9.27, the difference between the control models and the *no-terrain* stage actually tend to be more significant than difference from adding a faceted terrain and local air nodes. The physical difference between the original RadTherm building and the *no-terrain* stage in the rural scene is predominantly background terrain surface conditions, which are shown to be an important setting. Moving to the dense urban scene, the significance of local solar shading is demonstrated.

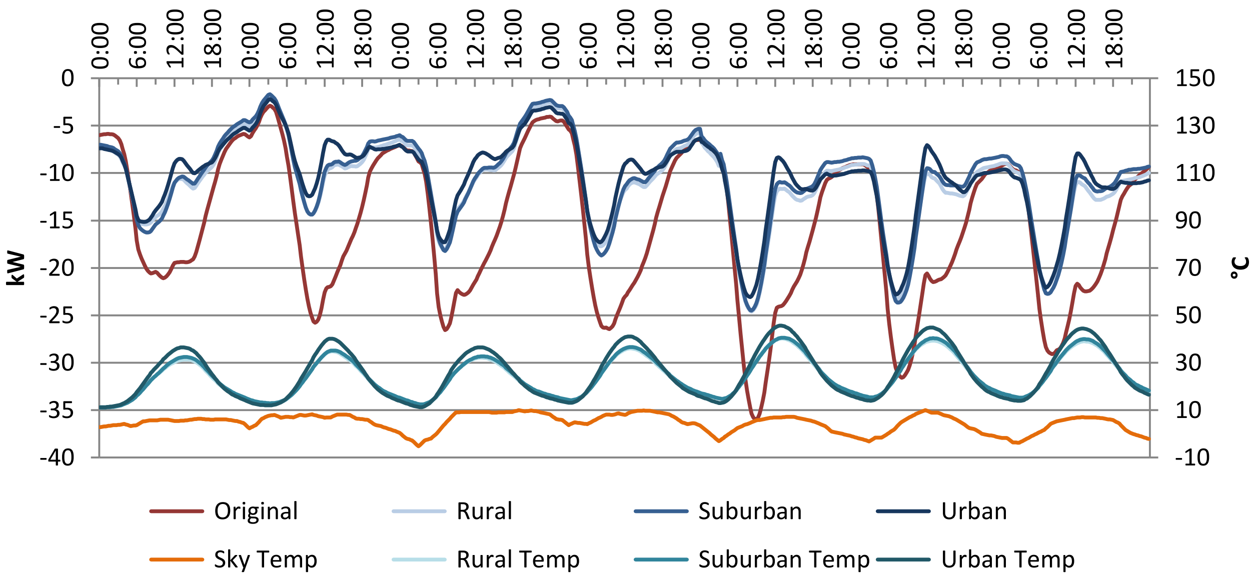
Figure 9.27 – Summer design week cooling totals



Although still quite small, the urban scene shows the greatest reaction to the terrain and microclimate stages. As expected, the inclusion of a faceted terrain does increase cooling demand. However the local air temperatures fail to rise above the ambient and the microclimate stage actually result in a decrease of cooling demand. This could indicate an error in the air flow model since convection heat rates are expected to remain constant without a change in local temperature, and may need to be investigated. However, differences in surface temperatures do not correlate with any particular wind pattern. Ultimately, a significant heat island effect could not be created.

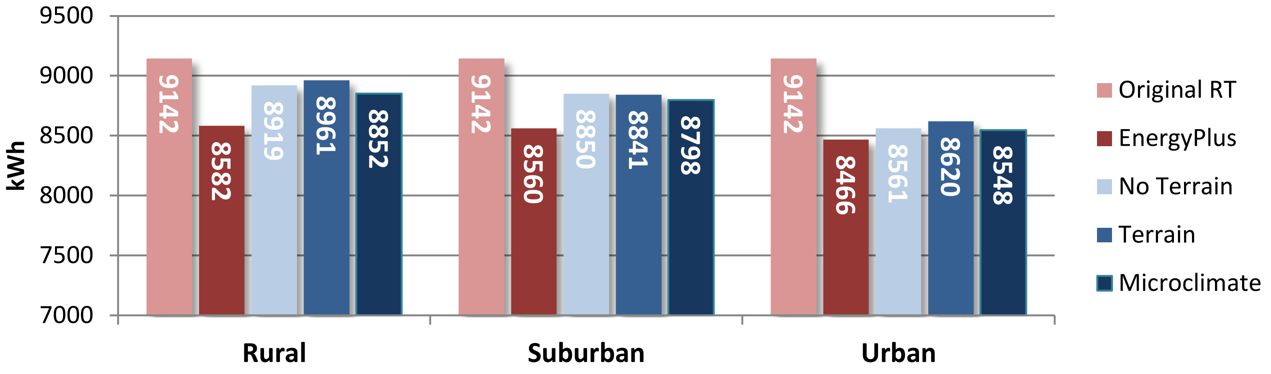
In Figure 9.28, a comparison of net radiation heat flow between each scene at the *microclimate* stage shows that the addition of the faceted terrain, which can reach temperatures over 20°C higher than the default background, makes a significant difference in heat rates. The differences between scenes however are small. This may be largely due to the lack of water content in the multi-layer soil part, preventing the grass terrain from absorbing more heat and making it more similar to the asphalt terrain model than they may be in actuality.

Figure 9.28 – Radiant heat loss and terrain temperature comparison between summer MC scenes



The annual simulations, shown in Figure 9.29 below as a sum of heating and cooling, show a significant and unexpected difference. The single building simulations in RadTherm are around 11% higher when heating and cooling are combined; however in every microclimate scene RadTherm less than 4%, and in the urban scene the difference is less than 1%. This is the exact opposite of what would be expected with the heat island effect. Additionally, the difference in energy demands from the original RadTherm building to the *no terrain* stage are similar to the differences between the other two stages. This lends to the argument that in these types of scenes, shading of direct solar radiation and the appropriate surface properties applied to the background are as critical to capturing microclimatic conditions as calculated surface and local air temperature.

Figure 9.29 – Annual energy totals, combined heating and cooling



For simulation run times, there is a considerable increase in EnergyPlus for the rural and suburban scenes. This is due to the solar reflection and distribution in the concave geometry of the trees. The increase in time to the *terrain* stage is caused by the increased thermal node count of the faceted terrain. The *microclimate* stage has a significant jump in times even though there are only four air nodes added from the *terrain* stage. There are considerably more time steps in the *microclimate* stage to handle the custom wind flow through the air nodes. During transition times of wind-to-no-wind and vice versa, the time step is dropped to either 1 minute or 15 seconds depending on the situation, which then occurs for 30 or 45 minutes before returning to the standard 15 minute steps.

The simulation times of the *no terrain* and *terrain* scenes could still be practical for industry use since they could be done as overnight runs. While not as convenient as a 10 minute simulation, being able to run a simulation overnight and review the results the next morning is still reasonable and commonplace in many engineering applications. At this point of development, the much longer *microclimate* simulations may not be as practical given the minor difference in results and the much longer simulation time. However, the urban microclimate model could still be completed overnight. In a research environment, these times could be considered acceptable considering that at this point there are possibly no annual microclimate simulations being conducted.

Table 9.22 – Annual simulation run times for all scenes and stages

	EnergyPlus	No Terrain	Terrain	Microclimate
Rural	5h 27m	7h 0m	12h 30m	21h 57m
Suburban	5h 4m	7h 4m	13h 42m	22h 28m
Urban	0h 10m	6h 9m	12h 47m	16h 14m

10 Discussion

While this study has been able to give a good demonstration to the power of RadTherm as a BES tool, the results from the previous chapter by in large show that the effects of calculated surrounding surface temperatures effect radiation gains greatly but have a relatively small effect on final energy demand. The lack of results in the energy demand could be considered a confirmation in the assumptions made in EnergyPlus. However now that a RadTherm BES model has been built and confirmed, there are future studies that may be more applicable to apply it to. This chapter reviews some strengths and weaknesses of this study, recommended improvements to the microclimate and BES models, and some comments on RadTherm's role in the BES/MC space.

10.1 Critique of the Microclimate Study

The results from the microclimate study show very little difference in energy demand between the various stages. Additionally, the largest factors on differences between the single building geometry and including the surrounding environment were related more to changes in solar gains than long wave radiation. However, the noted differences in terrain temperature and radiant gains shows that RadTherm can take this variable into account. Listed below are several critiques of this study that explore the unexpected results.

10.1.1 Urban Scene Geometry

The most notable shortcoming of the microclimate study is the failure to demonstrate a heat island effect. There are two items that could explain why this happened, both related to the scene geometry. The urban scene lacks construction of an actual urban environment. The materials are there, but the buildings are too small. To be able to make direct comparisons with the original RadTherm simulation, the target building construction had to remain constant in throughout the microclimate simulations. If a typical urban environment, with buildings 6-10 stories high were constructed around the target building, it would create a rather unusual scene resulting in unrealistic solar shading. This led to the surround building geometry being left at one story.

By building the urban scene with small buildings, there is a considerable lack of thermal mass and surface area to absorb and reradiate the solar gains. Many microclimate researchers focus on the urban canyon, where the outdoor spaces are relatively narrow streets relative the height of the buildings around them. Within these canyons, view factors to the sky are greatly reduced, which will increase the radiant effect of the terrain and vertical building surfaces on lower floors. So the first explanation for lack of a heat island effect could be a lack of adequate thermal sinks and geometry which enhance radiant heat exchange with the surrounding buildings.

10.1.2 Local Wind Velocity

The second explanation also relates to urban canyons, but this time the space between the walls. The results from the microclimate air node showed a very sensitive relationship between temperature and air flow. Even very low wind speeds (under 0.5m/s) are enough to replace the local air node volume several times during a 15 minute time step. In an urban canyon, there is a much greater chance of air becoming stagnant near the road surface and retaining the heat received from the buildings' exterior. The extremely simple air flow and convection coefficient models used in this study are clearly inappropriate for the urban environment.

10.1.3 Demonstration Building Construction

Another potential issue related to building construction relates to the target building. As noted in the Building Description section, the target building is built in the Passive House style. Passive houses are incredibly well insulated from the outdoors, making it a poor choice for demonstrating the effects of radiant heat exchange. If there is an increase in radiant heat to the exterior surface, the surface temperature will increase and transfer the heat into the building by conduction through the walls. The 400-500mm of foam insulation make conduction very difficult, thus making for a poor demonstration. A more appropriate demonstration model would be more akin to a common existing building.

10.1.4 Moisture and Humidity Content

Finally, while the interior humidity levels can be omitted with relatively little error to the energy demand, the moisture management in the microclimate is much more significant. One benefit of building microclimate models is to understand the effect of vegetation on local air conditions, and vegetation is able to dampen heat waves through latent heat transfer to the air. Additionally, moisture content and transfer in the soil adds thermal mass and behaviors that can vary considerably than dry soils.

TAI is reportedly adding moisture transfer to its human comfort models in mid-2012, which could possibly be leveraged for use in a microclimate model. Also, RadTherm does have a terrain part model that takes into account moisture content and 1-D transfer. This part type was not used due to the need to attach the terrain to a custom air node in the microclimate model, and changing the terrain part type would add a second variable. In a new study, tests should be run to determine the significance of the soil moisture content by comparing the terrain part type to the multi-layer. There is further discussion on moisture modeling in the Improving the Microclimate Model and - Recommendations to TAI chapter in the appendix.

10.2 Critique of the BES Model

The BES model in RadTherm has been built from scratch, which invariably results in a number of features being implemented on the basis of time rather than completing development. Listed below are three components of the model development or study which may need revisiting.

10.2.1 Mesh Resolution

The Mesh Resolution Test provided valuable results, but there were many more mesh models that were run and could not be used. This was due to the window geometry of the building, which could not be replicated with a wide variety of mesh sizes. The result was windows areas that did not match in all models, making all of the non-matching buildings unusable. Having those runs, particularly a run with a coarser mesh than 50cm x 50cm, could have been helpful towards the development of the meshing strategy. A more neutral or generic building would have been be preferred.

10.2.2 Simulation Times

While the mesh resolution test gave a glimpse into meshing strategy for buildings, the simulations run here are not indicative of actual building geometries. Run times will vary considerably with the addition of more facets and/or complex geometries. The simple nature of these models results in artificially low run times compared to a real case. A case study with real building geometry would be beneficial to understanding the actual performance of the RadTherm model in a commercial setting. The largest microclimate scenes are about 6000 facets and 24,000 thermal nodes, which is about as large as can be recommended at this point for run time and resulting file size.

RadTherm displays the run time used to perform every stage of its simulation calculations, making it very easy to measure performance. However, a number of the longer runs performed during the Mesh Resolution Test and Annual Simulation Methodology that were not used required unusually longer times than what was typical. This led to the discovery that the Windows and/or anti-virus task managers were performing background tasks during the simulation. RadTherm was never given top priority in the process manager, and thus it is possible that run times were altered by automated routines. How much the effect may be is unknown, however the correlation of times in the reported results appear reasonable and acceptable. This issue was resolved for the microclimate testing, and should be noted for future work.

It should also be noted that due to limitations in the RadTherm source code, not all parts of the BES/MC model could be parallelized for processing. Therefore, the simulations usually used only 25-35% of the total processor capabilities, usually maxing out around 50%. TAI has already reported that in a 2012 release, there will be improvements to the thermal solver that may decrease simulation times for certain models up to 10x. If the BES/MC model benefited from this improvement, and scripting was parallelized, simulation run times would be markedly improved and much more practical for larger, more complicated models.

10.2.3 HVAC Solver differences

Every effort has been made to reduce the differences between the HVAC models of RadTherm and EnergyPlus; however one distinct difference cannot be resolved. The HVAC solver in EnergyPlus is an integral part of the thermal solver and in RadTherm they are separate. The effects of this difference can be seen in the internal temperature graphs shown in the Mesh Resolution Test section above.

Many real world thermostats can only read the interior temperature of a zone, and modern energy management system will take several other readings like outdoor temperature. The researchers who developed EnergyPlus state that real controllers are able to sample conditions much faster than the characteristic time of the system, which results in near steady state interior conditions. (U.S. DOE 2011, p.8) Annual simulations can only sample interior conditions and discrete intervals that can be longer than the characteristic time and thus can lead to divergent solutions or unrealistic oscillatory results. In both programs, the equations controlling the heating and cooling have far more “knowledge” of the building than typical real world controllers do. While unrealistic, this helps to compensate for the long, discrete time steps.

While the controllers in each model are built on the same mathematical foundation, the interior temperature results are quite different. As already stated, there is an error due to ventilation rates not being updated in sync with the heating and cooling calculations which causes spikes in temperature. This error can and should be removed in future models. However, the other primary difference comes from a reactionary lag in the system. Every day there is a single peak and valley in temperature that corresponds directly to the solar gains. This could be a potential weakness in the model in that it is unable to adapt appropriately to changing conditions. More specific testing, physical validation and/or a more in depth study into thermal solvers are necessary to truly understand this difference.

10.3 Improving the Microclimate Model

Creating the microclimate model for this study seems like it has created more need for research and development than it has answered questions. The merging of microclimate models with building energy models is still relatively new, with a number of possible paths. Below is a listing of future work based on continuing development of the RadTherm model. Technical improvements to the software are reserved for the - Recommendations to TAI chapter in the appendix.

10.3.1 Revised AOI geometry

The first step in continuing development is to create more urban-appropriate AOI geometry. As was already discussed in the Critique of the Microclimate Study, built environment geometry which can replicate a heat island effect is necessary to test the model. The AOI terrain size may not need to be changed, but buildings which are 6-10 stories, more compact, and constructed in a manner which matches actual buildings would be most appropriate.

10.3.2 CFD Study to Develop Improved Convection Algorithms

In order to better understand the movement of air through the urban environment, a dedicated CFD study should be performed. Of course, no two cities are alike, and any specific CFD simulation is most likely not appropriate to use in other locations. This study would be targeted at developing wind velocity, flow, and convection coefficient algorithms which could then be used in a similar manner to the current model. RadTherm is capable of co-simulation with many commercial CFD codes, in which case accurate wind velocities can be calculated directly. However, as seen in previous studies, CFD simulations are extremely computationally expensive and prohibitive for annual or even transient cases. A catalog of general convective rules that can better capture the urban environment than the current methods used in EnergyPlus would be valuable for future heat island studies.

10.3.1 Moisture Management in Terrain and Exterior Air Nodes

Latent heat transfer was touched upon in the critique, but it is worth mentioning again. A proper microclimate model will need to have air node and terrain moisture content, along with latent heat transfer from terrain and vegetation as a critical feature. If the latent heat feature being added to RadTherm this year is flexible enough to work in the microclimate model, then development work can start without waiting for new features to be added by TAI. In the interim, simulations using the terrain part without the microclimate model can be performed to identify the significance of moisture content in the soil.

10.3.1 Air Node Structure

The air node structure that was developed for this project, while arguably still untested on proper urban geometry, is just one possible configuration. It is possible that only two nodes are necessary, or that more nodes can create localized hot spots. In conjunction with the CFD study, development work can go into developing a more refined microclimate air node model.

10.3.2 Co-Simulation with EnergyPlus

While RadTherm is technically capable of running simulations with complex building behavior and HVAC systems, it is not prepared to do so natively and would require a considerable development effort both in script libraries and source code to make it comparable. The work done by Yang et. al. (2012) described one method for connecting EnergyPlus to a mesh based solver, indicating that possibilities exist. This would leave RadTherm to be responsible for only the microclimate model, and pass on critical information to the more powerful BES model in EnergyPlus. Given the widespread popularity and acceptance of EnergyPlus, this method could also be more apt to take hold in the commercial environment.

10.3.3 Improved Vegetation Geometry

There was only a single type of tree geometry used in this study, and while it had a relatively low facet and thermal node count, its concave shape and repeated pattern noticeably slowed down simulations. It would be worthwhile to explore a wider range of vegetation modeling strategies with the goal of reducing simulation times. This could include single plants up to large gardens or forests depending on the AOI.

10.4 Improving the BES Model

In addition to understanding the solver differences outlined above, there are a number of improvements that could be made to the RadTherm model to make it more applicable to building energy simulations. Some of these are technical, such as adding convection coefficient or infiltration algorithms, while others are practical such as improving weather file or internal gains inputs. A full list of technical recommendations has been made for TAI and has been included as Appendix A. Practical improvements are listed below.

10.4.1 Additional Mesh Configurations

The methodology of the mesh resolution test is intentionally simple, and the results are a good introduction into the sensitivity of the model relative to the mesh. However, there are many more variables and possibilities in the construction of a mesh. A number of other mesh sizes were tested, however they were unable to exactly represent the window geometry, introducing another variable and thus the results were dismissed. One of these was a coarser mesh size (100cm x 50cm), and while the window areas are slightly different (window area difference <0.75m^2 per wall) the results are still very similar to all of the other models. This demonstrates the model's ability to accept even coarser meshes without losing accuracy and reducing run times further. The 100cm x 50cm model with single facet windows runs in 84-89s for a weekly time scale in winter and summer, respectively, compared to 277-292s for the final 50cm x 50cm model that was selected.

It is always the decision of the modeler to determine what type and size of mesh is most appropriate for their simulation. It would be a foolish exercise to attempt to give a single best mesh type to encompass every situation. Determining a meshing strategy is valuable, particularly when using the powerful meshing tools available. Further mesh resolution studies which leverage these tools would be valuable towards establishing an effective strategy.

10.4.2 HVAC Model

In the previous section, working towards integrating RadTherm with EnergyPlus in a co-simulation is suggested as a way to improve the BES over building all of the same features into RadTherm directly. However, having a basic HVAC model in RadTherm directly may still be beneficial to urban planners or architects who may not need the power of EnergyPlus but still need to know how energy demand is affected by city design.

The integration of the HVAC model with the thermal solver has been noted above, with issues related to ventilation and reaction times of the heating and cooling. Further work should be done in the controller of the heating/cooling model to improve on these differences from EnergyPlus. The spikes in ventilation could be improved by changing the timing of the update to advection links and/or the heater scripts. Another possible method would be to include integral and differential controls to the current proportional only method.

10.4.3 ASHRAE Standard 140

ASHRAE Standard 140 (ASHRAE 2011) is a methodology for comparing building energy simulation programs. It consists of a collection of building geometries, weather files and testing conditions which are considered to cover all or most of the interesting physical properties of a building and/or the HVAC system. Because simulation programs do not all have the same features, the tests are dividing up such that individual features can be omitted.

The standard was unfortunately discovered too late in the study to be applied; however it does not compromise the quality of the results of this study in any way. The standard makes clear that it is not intended to validate simulation models or prove an acceptable result, but instead provide a method of comparing models. There are no real world testing results to compare to, only the results from other models. There are no guidelines or criteria for determining an acceptable result either, instead leaving that up to the modeler or certification agencies. So the standard is basically a number of predefined benchmarking tests, and it saves the user time by providing results from a number of other programs for comparison.

While it does not offer anything in the way of model validation, it would be worthwhile to perform the test for comparative reasons. Interestingly, the models compared have a very wide range of results. For example, annual heating loads vary between 16-50%, cooling loads between 27-177% and transmitted solar radiation values between 14-25%. Even the minimum differences are much wider than seen anywhere in this test, and knowing where RadTherm falls in this group would be worthwhile. It should be noted that EnergyPlus is not one of the programs tested, however one of its predecessors, DOE-2 is.

On a related note, ASHRAE does have an analytical testing method developed through internal research projects initiated by the DOE explicitly to validate EnergyPlus. (Henninger and Witte 2011) However, this method is still analytical rather than empirical, and empirical testing would be arguably more valuable.

11 Conclusions

This study set out to improve the way building energy simulation programs manage the interaction with the local environment which surrounds the target building. To do so, a high powered thermal solver has been sought, RadTherm from ThermoAnalytics, which can handle the radiant and convective interactions with surrounding geometry, as well as model an energy supply system.

The first objective was to establish that RadTherm has the necessary features and tools capable of building energy simulation. A complete description of the model construction is presented, as well as the tests performed where it is benchmarked against the well accepted industry standard, EnergyPlus. The results show that RadTherm produces heating and cooling demand curves that over an annual time frame are accurate to within 6%, have a correlation coefficient over 0.98 and have an NRMS of less than 3%. These results are well within the prescribed acceptance tolerance and establish RadTherm as capable BES software.

Using the qualified BES model, three scenes are created with the target building at the center for the purpose of demonstrating the significance of microclimate on energy demand. Two components of microclimate are highlighted; radiant heat gains and local air temperature. The RadTherm model is capable of showing a drastic difference in net radiant heat rates of up to 50% when modeling surrounding environmental geometry. The local air temperature model is extremely sensitive to wind, and therefore only shows deviations from ambient air during times of no wind driven air flow.

The annual energy demand is shown to vary with the added microclimatic features, however total difference is less than 1%. This shows that for the scenes modeled in this study, the simplified assumptions made for long wave radiant exchange in EnergyPlus are reasonable. However, given the documented existence of heat island effect, there are scenes in which these assumptions will not hold. Therefore, a collection of additional work has been suggested, the most significant tasks being;

- Build a new urban AOI that is representative of a more realistic city. This includes buildings which are 6-10 stories high, streets 10m wide, and envelope construction matching common buildings,
- Conduct a CFD study to develop a generic model of wind behavior in dense, urban environments. This work would go into refining the current wind flow and convection coefficient algorithms, and
- Test the terrain part in simulations with the standard wind model to understand the role of moisture in natural terrain.

The changes in energy demand as a result of the microclimate demonstrate, even if the scale is small relative to the effects of shading and surface properties, that the basic structure of the RadTherm model is sound. With building geometry built to highlight the heat island effect, RadTherm is expected to calculate a more significant response in energy demand due to radiant gains than what has been presented here. The response could be even greater with development of more appropriate convection algorithms for the urban environment.

For use in industry, the considerably longer simulation times in RadTherm do make it less practical on an annual time scale, meaning more effort in reducing mesh counts is needed to improve run times. The model may be limited to a research environment in the short term, in which case simulation times are much better than any other models using CFD. Ultimately, the modeling procedure presented here is a valuable first step in the design of BES/MC simulations and should be developed further.

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Appendix A - Recommendations to TAI

As a side project to the primary thesis study, software development recommendations have been noted throughout the modeling process. The recommendations are be geared towards features which can make RadTherm comparable to and competitive with interfaces offered with typical building annual simulation programs. Many settings and features common in modeling tools custom built for the task are missing in RadTherm, and therefore must be added through a unique combination of scripting and curve manipulation. Integrating these tools into RadTherm would be very helpful to gain a foothold in this part of the building energy modeling sector.

There is also the option of co-simulation RadTherm with EnergyPlus, in which case all of the building specific features would not be necessary. Instead, development efforts would need to be focused on creating the appropriate linkage between the programs done through a free tool from Lawrence Berkeley National Lab, the Building Controls Virtual Test Bed. Co-simulation allows development of RadTherm to focus on its strengths while borrowing the strengths of EnergyPlus. It could also be easier for users to consider RadTherm an add-on tool rather than a replacement tool.

Both directions have their merit, and the recommendations below have comments on how they apply to each of them. I should also be sure to state that my assumptions or impressions of the "industry" are simply based on how I've used BES programs and what types of improvements I would like to have. Certainly, customers are the only ones qualified to identify which features are most worthwhile.

A.1 Refined Basic HVAC Model

While the co-simulation option may be preferable for engineers more focused on the detailed building design, a basic HVAC model similar to the one used here would be worth refining and implementing into a script package in RadTherm. This model would be targeted at users who are more interested in the urban design aspect of the microclimate model and would be better served by a simple, integrated tool over co-simulation. RadTherm could also be a great tool for researchers or architects who want to develop and implement passive heating and cooling techniques. In that application, the whole point is to eliminate the need for HVAC as much as possible, so there is less need to spend lots of time and money developing or integrating with an HVAC model as complex as EnergyPlus.

With that said, there is still some basic level of HVAC that needs to be included in order to make the simulations work. For the most part, this is the model I have developed through this thesis. I will say that this model is going to need to be scrutinized and rounded out by people with more programming experience than myself, but I do think that the methodology is a good foundation for a future RadTherm plug-in. The functional issues described in the Improving the BES Model section must also be worked out.

I can picture the HVAC add-on simply being a function library much like the battery or human comfort libraries that must then be appropriately applied to create the desired HVAC system. In this way, development work is minimized and the features are integrated directly into the existing RadTherm architecture. I do think that very solid support literature will be necessary to ensure customers are implementing the tools correctly, but once the methodology is learned and understood, it would become a natural part of using the software.

A.2 Co-Simulation with EnergyPlus

As already mentioned at the start of this appendix, there is a free tool available for linking EnergyPlus with outside programs. The methodology of linking EnergyPlus with ENVI-met is also a good head start for planning how linking with RadTherm could occur. (Yang, et al. 2012) There are some challenges in transferring the properties of a meshed, multi-node surface to a single node surface as in EnergyPlus that are described in the paper. However, RadTherm geometry can handle angles and curves better than ENVI-met since it is not using a fixed orientation mesh for CFD. Enabling this link up could be a very big starter for many BES focused users if some demonstrated advantages (i.e. urban heat island) can be done in RadTherm.

A.3 Air Nodes

There are a few features that RadTherm currently lacks that might be nice to add when considering a stand-alone HVAC package. In EnergyPlus, air nodes are handled automatically within the solver and are based on zone geometry. In RadTherm, the user is required to create all of the air nodes they need in the simulation and associate them manually. This process could lead to issues if/when geometry is modified and the air nodes are not. In many cases, a proper methodology using defined air node positions and convection links using “nearest defined fluid” may make this a non-issue. At this point, I am only using a single zone with a single interior air node, so it is difficult to comment exactly how a robust air node network could/should be created. When it comes time to handle multiple zones, I can foresee some extra effort being required to ensure the air nodes are appropriately managed.

One issue that came up during HVAC scripting is the lack of ability to reference the volume of an air node. This value is used in determining the amount of stored energy in the air node, but is currently entered manually as a constant value in the script. A good first step would be to add an api that allows reading of the air node volume. A better second step would be to somehow calculate the volume of the air node automatically. If building geometry is being modified frequently, it would be very easy for the user to forget to update the zone volume and throw off the simulation results.

I should mention that the administration of air nodes is largely an issue for multi zone models. This study never got past the single node zone, but even then there was a noteworthy amount of effort to ensuring the air nodes were assigned appropriately. The single zone model is not representative of the vast majority of buildings and a lot more will be learned about the strengths and weaknesses of RadTherm’s air models when a multi-zone building is created.

I think I’ve hit moisture content enough times that I won’t go into it much again here. TAI has already identified the important of this for interior air in the human comfort model. As described in the paper, it is important for the microclimate model as well. My impression is that adding it as a property of the air node, similar to temperature, density or enthalpy, would be the most beneficial. Then it can be used in api scripting in future model construction.

A.4 Geometry editing

For the vast majority of architectural professionals, AutoCAD is the default program for creating building geometry. While relatively new, Google SketchUp has also emerged as a popular building modeling tool. Given the dominance of these tools, most (if not all) building energy simulators have the ability to import geometry in at least one typical building industry file format (i.e. *.dxf, *.3DS, *.obj). RadTherm is similarly capable of importing 3D geometry; however it has the added requirement of being in the form of a mesh. This requires uses to have an intermediate tool, particularly one which is somewhat foreign to many in the building industry. Any attempt to simplify this process is worthwhile. I cannot claim to understand the details of how mesh generators operate, or the complexity of integrating one into RadTherm, but a very convenient process would be to have a mesh generated during the geometry import process into RadTherm.

Even though the majority of geometry is often created outside of an energy simulator, there are many times when users will want to modify geometry on the fly. This could be to test different design options, make simple corrections, or just to save time over going through the import process again. Geometry creation in RadTherm is, to be completely honest, a fairly painful process. It seems clear that the intention with this tool is to do the vast majority of geometry creation and editing outside of RadTherm. When considering the complex geometry of vehicles this makes sense, however the simplicity of most buildings makes in-program geometry editing more desirable, particularly for users who don’t already own a meshing tool.

A.5 Materials

Ideally, the user of a BES program would have access to all of the material properties they needed. Of course, a 100% complete library can never be compiled, but at this point the RadTherm library seems to be lacking in building specific materials. There are obviously building materials available, but not nearly as many as dedicated programs. Given the extreme similarity to a number of materials in other libraries, it may be completely unnecessary to have such an extensive list, and a library with too many materials can and does cause confusion. It might be worthwhile to contact a building materials group or review competing products libraries and compile a listing of critical building materials to be added to RadTherm or offered as a package. A number of organizations keep materials standards on file, including a few listed in the Materials section above which were taken from DesignBuilder.

There is also a limitation in the construction of windows that should be addressed. The only fluid RadTherm permits to be used in a multi-layer part with transparent layers is air. Many windows available today have argon or krypton gas between panes, and RadTherm should be updated to be able to create these parts. Al did suggest the possibility of using a vacuum to represent the noble gases, which could be a worthwhile endeavor. A quick comparison study with EnergyPlus would be able to determine the validity of that approach.

One critical value that building designers and engineers use consistently is U-value, or the components ability to resist heat transfer. U-values are typically not used during simulations, but being able to conveniently read the U-value as a property of a part would be a very convenient feature for most users.

A.6 Weather File

The requirements for annual weather are very different from the situations in which RadTherm is typically used, and thus it would be beneficial to modify the process for creating and or reading weather files. As described in the TMY2 for RadTherm section above, the process of bringing a standard building simulation weather file into RadTherm is rather complex. Of course, this was the first time going through the process and thus required some customization of tools that can now be used relatively quickly. However, dealing with a third party code is still a somewhat clumsy process that could be streamlined. The *.epw file is not too incredibly different from a standard RadTherm weather file. It would be very convenient if RadTherm was simply able to read the *.epw file directly. It is a widely accepted and used file format for weather in building energy simulations, meaning acceptance and understanding from the industry comes built in, and it's free to use. This is important for both development paths.

A.7 Schedules

The ability to create schedules within RadTherm will almost certainly be a necessity going forward to appeal to building modelers. Schedules are necessary for the application of internal heat gains from various sources, building occupancy, and air flow through the ventilation system. Thus far, curves are an adequate way of applying the gains and air flow schedules to the model. So a schedule generator could potentially be a way of creating curves, much like the tool I've created in Excel but instead built into RadTherm. The user is then tasked with applying the curves to the appropriate locations. A completely seamless and integrated scheduling tool may be ideal, but I feel a curve generating tool would be perfectly acceptable.

Another option is to simply have default curves built in for a few common scenarios. This could be a way to avoid unnecessary programing and still meet the needs of people using RadTherm as a standalone BES/MC tool. Chances are those users are not going to need an extremely power scheduling tool anyway, and generic defaults could be enough to satisfy them.

A.8 Air Nodes on Terrain Parts

My understanding is that the TAI terrain model is quite powerful, and I was disappointed not to be able to use it in this study. Given time, I would have done some runs using the terrain part in the rural scene to compare to the multi-layer part. As I've described above, the reason I didn't use it is because I needed the customization offered in attaching an air node. If terrain parts could get the same ability, it would improve the microclimate modeling processes. Ground modeling is becoming a hot topic in the BES world, and one reason is for microclimate models.

A.9 Parallel Processing on Scripts

I had mentioned to Steven at one point that it was interesting I never had over 50% (2 cores) of processor being used at any given time. He pointed out that not all parts of the code had been parallelized, and scripts were one of them. I'm sure there is a long list of items that are due to be parallelized, but just noting that run times could have been much better had the full processor been usable.

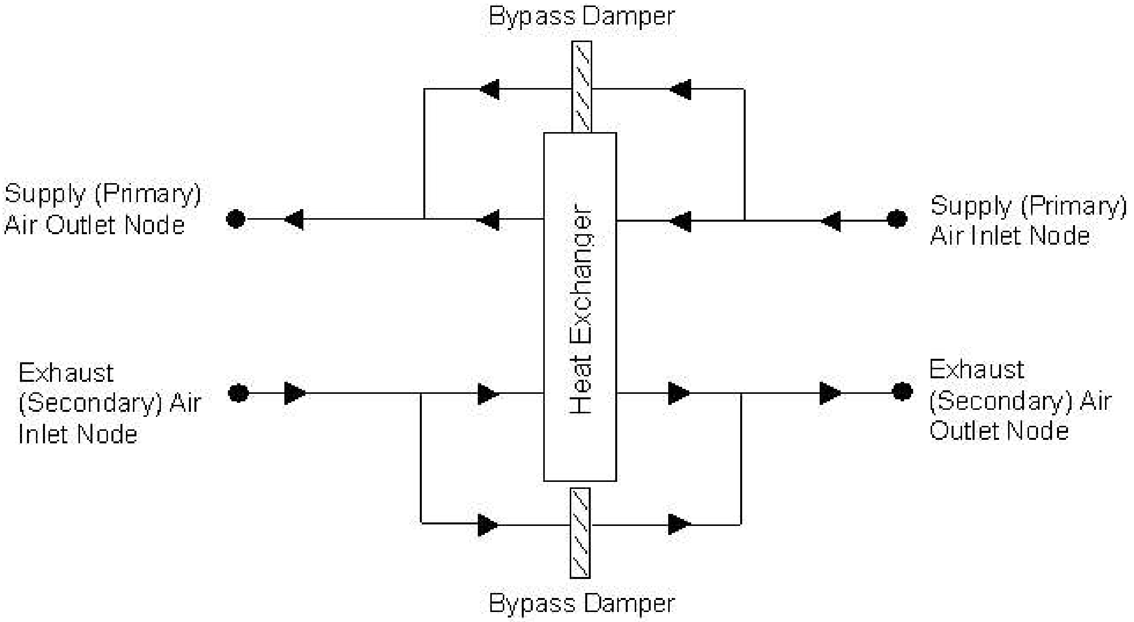
Appendix B - Heat Exchanger Model

Heat recovery units are capable of offsetting a large portion of heating loads by preheating incoming ambient air with the room temperature exhaust air. The air-to-air heat recovery model is well described in EnergyPlus documentation, and thus should be easily to replicate. (U.S. DOE 2011, p.801) A full description of the model as it exists in the documentation will be provided, the limitations of the model by DesignBuilder, and the issues experienced in programming an equivalent model in RadTherm.

B.1 Model Description

The behavior of an air-to-air heat exchanger is based on its effectiveness, the temperatures of the two streams, and the flow rate of each stream. A diagram of a typical heat recovery system is shown below in Figure B-1.

Figure B-1 – Diagram of an air-to-air heat recovery system (U.S. DOE 2011, p.801)



The effectiveness is primarily governed by the design of the heat exchanger. Modern heat exchangers are now reaching efficiencies (effectiveness x 100%) of over 90%. However, when considering a single heat exchanger, the effectiveness also varies linearly with air flow rate by a considerable amount. Effectiveness tends to be higher with slower air flow rates, with most units having a lower and upper limit. The ARI has a standard method of creating an effectiveness slope, using temperature measurements at 100% and 75% flow rate capacity. (U.S. DOE 2011, p.802) These measurements can be put into EnergyPlus, however DesignBuilder does not offer this input and instead asks for a single effectiveness value that remains constant at all times.

With an effectiveness determined, the incoming temperature and flow rates of each air stream are needed to calculate the outgoing temperatures. The relationship is defined by the equation;

$$T_{fo} = T_{fi} + \varepsilon\left(\frac{\left(\dot{m}\cdot c_p\right)_{min}}{\left(\dot{m}\cdot c_p\right)_{frsh}}\right) \times \left(T_{ei} - T_{fi}\right)$$ Equation [B-1]

T_{fo} = fresh air temperature leaving the each exchanger (°C or K)

T_{fi} = fresh air temperature entering the heat exchanger (°C or K)

T_{ei} = exhaust air temperature entering the heat exchanger (°C or K)

ε = effectiveness

$(\dot{m}c_p)_{frsh}$ = heat capacity rate (mass flow rate times heat capacity) of the fresh air stream (W/K)

$(\dot{m}c_p)_{min}$ = minimum heat capacity rate (mass flow rate times heat capacity) (W/K)

All terms in Equation [B-1] are readily available to solve for T_{fo}; T_{fi} is the ambient air temperature supplied in the weather file, T_{ei} is the air temperature leaving the zone, and effectiveness is a user input as described above. Heat capacity rates are dictated by air flow rates and temperatures (driving density and heat capacity) which are all known values. In EnergyPlus, the air flow rate entering and exiting a zone is assumed to be equal. In a single zone model, this means the exhaust air flow rate is the sum of the incoming plus infiltration. The rest of the variables are determined with determined air properties.

Once an exit temperature is determined for the fresh air, a power rating can be calculated. The power rating makes it easy to determine the value of the heat exchanger since the power supplied is power the heater does not have to provide. The equation for power is;

$$\dot{E}_{he} = \dot{m} \times c_p\left(T_{fo} - T_{fi}\right)$$ Equation [B-2]

$\dot{E}_{he}$ = heat exchanger power (W)

$\dot{m}$ = mass flow rate of the fresh air (kg/s)

cp = heat capacity of the fresh air (J/kg-K)

T_{fo} = fresh air temperature leaving the each exchanger (°C or K)

T_{fi} = fresh air temperature entering the heat exchanger (°C or K)

B.2 RadTherm Model

The model scripted in RadTherm follows the calculation steps described above to determine the power rating that should be applied to incoming air. To apply the power, a geometry-less air node is created with an upstream advection link to the ambient air (downstream it is connected to the heater air node, discussed in the following section). The scripts are run and the appropriate heat rate is imposed on the air node, preparing it for delivery to the heater node.

At time of writing, there are two primary issues with the operation of the model. First, the calculated temperature (and thus power rating) are much higher than what EnergyPlus is calculation. DesignBuilder only reports the power rating of the heat exchanger, which is easily back calculated to determine the output temperature using Equation [B-2] above. The output temperatures are about half of what is calculated in the RadTherm model. This issue is very unexpected since the equations are based on EnergyPlus documentation. Further research is required to determine the cause of the discrepancy.

The second issue concerns the application of power to the air node. When examining the temperature of the air leaving the heat exchanger node, it is different than the temperature calculated to create the power setting. There are times when the temperatures match, however the difference is often two or three degrees Celsius. Again, further research is required to determine the cause of the discrepancy.

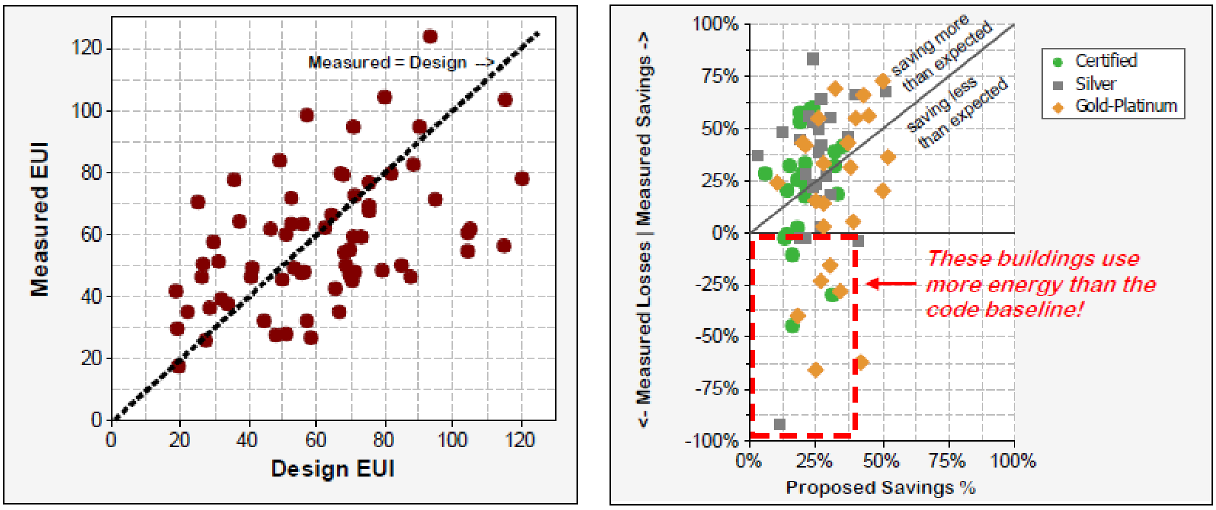
Appendix C - Condensed Paper for Conference Submission

C.1 Introduction

In light of the recent research on humanity's impact on the environment, atmosphere and natural resources, a movement is growing to reduce energy consumption in the built environment. Buildings account for over 35% of the energy demand in OECD countries, making them a prime target for improvement. (EIA 2011) There is a vast array of building energy simulation models in existence, many with a specialized purpose. (Crawley, Hand, et al. 2008) (Al-Homoud 2001)

Models of all types inherently require some level of simplification, ultimately leading to error. However, the incredibly complex nature of buildings and the difficulty of modeling them are leading to excessive error. A 2008 study revealed that LEED certified buildings often have a considerably different energy demand in operation than what was predicted during modeling. (Turner and Frankel 2008) In Figure 1.1, the chart on the left shows that actual usage can vary by up to 30%, and the chart on right shows that while many buildings perform better than expected, many are worse and sometimes even worse than the baseline energy code. The source of these errors is not explicitly known, and while they could be due to a misrepresentation of the use of the building there are physical assumptions left out in many models that could also be to blame.

Figure C-1 – Modeled vs. actual energy demand in LEED certified buildings (Turner and Frankel 2008)



The most common and popular building simulation tools use standardized weather inputs as a boundary condition surrounding the structure of interest. These weather inputs are typically collected at locations far removed from the built environment, most often at airports. Urban landscapes are known to have a significant effect on local environmental conditions, particularly the heat island effect. BES programs often take simple shading and radiant effects into account, however the target building does not interact with the surrounding environment and thus the microclimate condition cannot be modeled. (U.S. DOE 2011, p.52) By omitting this microclimatic variable, BES programs are accepting a significant source of error in urban environments. (de la Flor and Dominguez 2004) (Santamouris, et al. 2001)

Several studies have attempted to bring the microclimate variable into building energy simulations with various methodologies. Oxizidis et al. (2008) used a synthetic weather generator to capture urban heat island effects, but it could not handle local convection variables. He et al. (2009) built a complete thermal solver into a commercial Japanese 3D-CAD program, which also did not take local convection into account. Mochida et al. (2006) used a co-simulation technique with CFD and TRNSYS; however it was focused on interior environmental conditions. Yang et al. (2012) created a custom co-simulation technique using EnergyPlus and ENVI-met, but has only presented a methodology without results. Bouyer et al. (2011) use a custom thermal solver co-simulated with Fluent CFD code where they identify the significance of each type of microclimate interaction, concluding that local IR radiant and convective heat fluxes are significant and cannot be ignored when doing building energy simulations.

Another option to handle microclimate simulations is RadTherm from ThermoAnalytics. (ThermoAnalytics 2010) RadTherm is traditionally used in defense and automotive sectors, but has been identified as a relevant tool for building physics studies because of its radiant exchange model. (Kapur 2004) RadTherm has been examined before for use in building energy simulations with noted advantages over current art, however being a more fundamental thermal solver it is limited by a lack of building sector specific features. (Sami and Gassman 2006) (Lahti and Lindberg 2006) This limitation can be overcome because, much like TRNSYS, it has a scripting shell that allows engineers to custom build functions that can interface with the core solver.

C.2 Objectives

There are two objectives of this study; first is to establish the legitimacy of RadTherm as a building energy simulation tool. There have been building simulations done with RadTherm, however nothing on an annual time scale and to author’s knowledge none with an integrated HVAC system model. The second objective is to demonstrate the importance of microclimate modeling in annual building energy simulations. Microclimate models have been done before as noted above, however all prior examples are done with time scales less than one year. Most of the common building rating systems require annual simulation lengths, and thus this time scale is most relevant for determining the absolute performance of a building or urban planning scheme.

C.3 Methodology

This study is constructed as a combination of two smaller studies, which work together in succession to achieve the objectives. A BES model must first be constructed in RadTherm. A number of simulation tools which are native to most building modeling tools are not in RadTherm, and therefore must be custom built. Once a BES has been created, then scene geometry is built up around the single building model and a local air node network constructed. Baseline criteria are necessary to ensure the RadTherm model is relevant, therefore EnergyPlus has been selected as a control and will be accessed through the commercial add-on DesignBuilder.

C.3.1 Building Energy Simulation

Materials, internal gains, HVAC and weather boundary conditions are done in RadTherm such that they are equivalent to EnergyPlus. Building geometry is based on the Passive House standard and created independently in each program with no discrepancies between them. RadTherm is a much more universal program, and thus does not have as many building specific features as DesignBuilder. Therefore, HVAC control and internal gains models are built through the use of RadTherm curves and scripts, which can be integrated with the thermal solver. The design of the models is described in further detail below.

C.3.2 Microclimate Model

Demonstrating the significance of modeling microclimates is done by comparing the effects of adding surrounding environmental features in each BES program. RadTherm accepts weather inputs and applies them much in the same way EnergyPlus does. However, RadTherm calculates radiant exchanges anywhere in the model, whereas EnergyPlus only considers ground and sky temperatures, assumes the ground is the same temperature as ambient air, and has a default emissivity for all objects outside the target building. Radiant heat rates to the building's exterior can be read in RadTherm, thus the actual radiant effect the surrounding environment can be measured.

The second significant component to the microclimate is local air temperature. Neither program by default can modify the ambient weather file; however RadTherm has features which can simulate local weather with customized air nodes. A network of air nodes are used to create a local air environment around the scene geometry, which then interact with the ambient weather. Prior to entering the AOI, the ambient air will be pre-treated as if it has passed through 5 km of terrain similar to the AOI.

Within each program, three scenes are built. The first scene is rural, where no additional buildings are added, only trees and the terrain is entirely covered in grass. Scene two is suburban, with a looser building grid, a mixture of asphalt and grass on the terrain, and trees added. Scene three is urban, with buildings placed in a dense grid around the target building and the terrain between them asphalt. The same target building used in model development is placed at the center of the scene and remains constant throughout the study.

EnergyPlus has a single model for each scene, whereas features in RadTherm are added in stages in order to identify which component of the microclimate has the greatest effect. The first stage is to update the default background and add the surrounding buildings and trees. The two programs are most similar at this stage. The second stage is to add a faceted terrain, which models dynamic radiant exchange and more realistic ground modeling. The third is to add the air nodes to create a local air temperature within the scene.

C.3.3 Validation Criteria

To validate the RadTherm model, a reputable reference case is necessary. EnergyPlus is the benchmark model, and tolerance criteria are applied to the results created by it and RadTherm to determine the appropriateness of the RadTherm model. These parameters are used to qualify the RadTherm model during BES development. The microclimate modeling is expected to show significantly varied results since it cannot be recreated in EnergyPlus, but the same statistical measurements are done as a measured reference.

There are three parameters of interest that will be used to determine the acceptability of the RadTherm results; total energy difference, the correlation coefficient, and the NRMS. The total energy difference is simply the percentage difference between the summations of predicted energy demand from RadTherm to EnergyPlus. This is represented by Equation [C-1] below. For a RadTherm simulation to be considered valid, the total energy difference must be within 10%.

$$\Delta E = 1 - \frac{\sum E_{rt}}{\sum E_{ep}} \times 100\% \qquad \text{Equation [C-1]}$$

E_{ep} = total energy demand for a given time frame by EnergyPlus (kWh)

E_{rt} = total energy demand for a given time frame by RadTherm (kWh)

The correlation coefficient is used as a measurement of how well the pattern of two data sets matches each other. The correlation coefficient is calculated using Equation [C-2], and must be higher than 0.9 to be acceptable.

$$C(X,Y) = \frac{\sum(x-\bar{x})(y-\bar{y})}{\sqrt{\sum(x-\bar{x})^2\sum(y-\bar{y})^2}} \qquad \text{Equation [C-2]}$$

x = data point in a RadTherm set

$\bar{x}$ = mean of a RadTherm set

y = data point in an EnergyPlus set

$\bar{y}$ = mean of an EnergyPlus set

Two data sets which are perfectly correlated can still have completely different values, and therefore a parameter is necessary to determine what level of deviation is present. The normalized RMS is a measurement of average deviation between two data sets, which is then divided by the total range of values in the target data set, resulting in a percentage. The NRMS value is determined with Equation [C-3] below, and also has an acceptability limit of 10%.

$$NRMS(X,Y) = \frac{\frac{\sqrt{\sum(x-y)^2}}{n}}{x_{max}-x_{min}} \times 100\% \qquad \text{Equation [C-3]}$$

x = data point in a RadTherm set

y = data point in an EnergyPlus set

n = count of data points (equal in both sets)

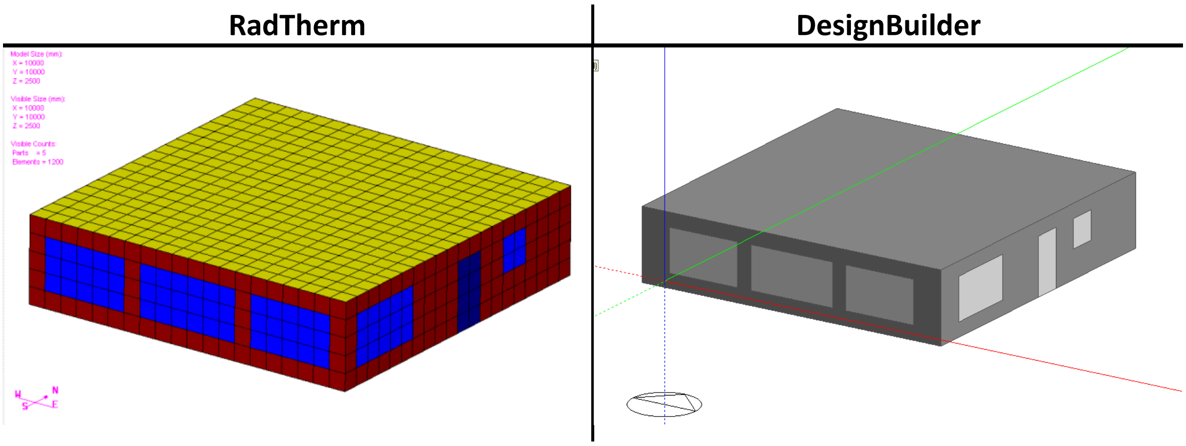
x_{max} = maximum data point value in the RadTherm data set

x_{min} = minimum data point value in the RadTherm data set

C.4 Model Description

This chapter describes the model geometry being used, the BES and the microclimate air models in RadTherm. The target building is intended to be a very simple residential use structure having a single zone and Passive House construction with no thermal bridges and very low infiltration. The location is arbitrarily set for Stockholm, Sweden with weather data from Arlanda Airport. In Figure 4.1 below, screen shots of the building are shown from each program.

Figure C-2 – Images of the target building model in each BES program



RadTherm

DesignBuilder

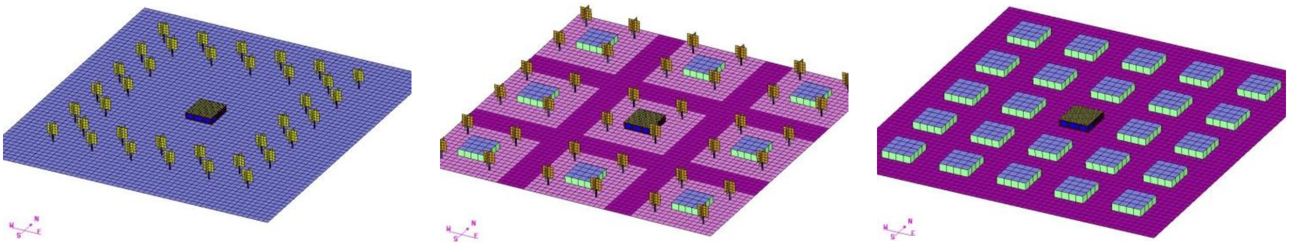
RadTherm has a built in script function which allows parameters to be read in from the thermal solver to perform routines, which can then be feed back to the thermal solver. The steady state heating/chilling condition can be simulated in RadTherm by solving the heating or cooling rate based on the heat balance of the room. The air in the room is assumed to be perfectly mixed, thus having the same temperature throughout. The methodology for solving heating and cooling power, as well as infiltration, is based on the calculations used in EnergyPlus. (U.S. DOE 2011)

C.4.1 Microclimate Model

The scenes built up around the target building are demonstrations of common built environment landscapes. The terrain is a flat plate, 110m x 110m x 0.5m in size with multiple layers to represent asphalt and grass parts. Due to a technical restriction in RadTherm, the terrain model used does not include moisture content or transfer. The surrounding buildings are of the same size as the target, but have no windows or doors and facades made entire of brick. This simplification allowed the used of less mesh facets for faster run times. The tree model consists of a trunk and leaf portion which in total stands 4.5m high. The leaf parts are set to be transparent, allowing 10% of the solar radiation to pass through.

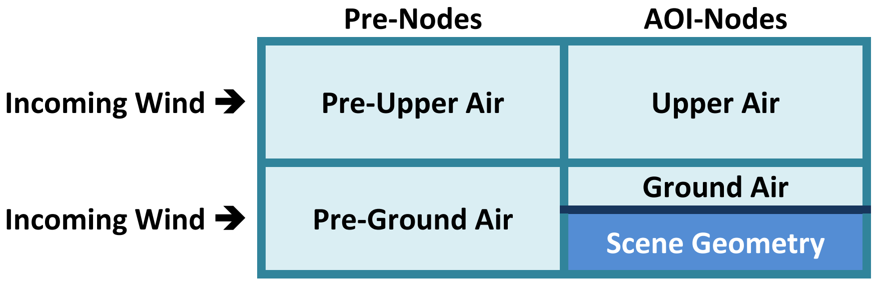
There are three environments which the target building has been placed; rural, suburban and urban. The rural scene only has the target building, sitting on a grass terrain and surrounded by two rows of trees 25m away. The suburban scene has eight surrounding buildings placed 30m from the target, each sitting on a 30m square grass terrain. Between each lot is asphalt road. There are also four trees around each building, set off the corners at a 45 degree angle and 4m from each wall face. The urban scene has 24 surrounding buildings set in a grid pattern with 10m between each building. The terrain between them is asphalt road. Images of each scene are shown…

Figure C-3 – Images of each microclimate scene in RadTherm (L to R; rural, suburban, urban)



To replace the default wind model in the *microclimate* stage, a collection of air nodes connected by advection links are used to represent the local air in the AOI. There are four nodes in total; the air at the ground level in contact with all AOI surfaces, the air volume directly above the ground node, and pre-conditioning air for each node over the AOI. This arrangement with identifying names for each node is represented in Figure C-4 below. The AOI-nodes are to represent only the air that is directly above the AOI, with the ground air node set at 3m in height, and the upper air node at 4.5m, giving a total height of 7.5m.

Figure C-4 – Diagram of the microclimate air node model



The air node heights are an important variable in determining air flow. To account for the difference in wind speed between met towers and sites, the wind speed modifying algorithm from EnergyPlus has been used in the RadTherm microclimate model. (U.S. DOE 2011, p.54) Final wind speeds are based on terrain conditions and the height of the zone. The modified wind speed is then multiplied by the frontal area to determine a volumetric flow rate. To account for vertical air exchange, advection links are made between the ground and upper nodes over the AOI as well as the pre-nodes. As a simplification, the vertical air mixing is set as a constant 5% of volume.

The pre-nodes have been included to condition the incoming air as if it has passed over a stretch of terrain exactly like the AOI, only many times larger. A multiple of 45 is used, meaning the pre-nodes are 45 times larger in volume than the AOI-nodes and effectively represent 5km of terrain outside the AOI. To condition the air, the net convective heat rate is read from the AOI-nodes, multiplied by 45, and then imposed on the pre-nodes.

C.5 Results and Discussion

C.5.1 BES Model

The single building energy model test resulted in acceptable performance for all criteria. The RadTherm energy consumption was nearly the same in winter design week, relatively low in the summer design week. In the annual simulations, both heating and cooling totals are about 5.5% above EnergyPlus. In all cases the correlation is very high, and in the NRMS relatively low in the annual case. The total energy differences here are valuable for comparisons in the microclimate study as base relative performance.

Table C-5 – BES results from both design weeks and annual simulations

	Winter Design Week		Summer Design Week		Annual	
	EnergyPlus	**RadTherm**	**EnergyPlus**	**RadTherm**	**EnergyPlus**	**RadTherm**
Total Heating	250.8	253.1	-	-	2818	2981
Difference	-	0.92%	-	-	-	5.79%
Total Cooling	-	-	484.9	450.1	5841	6161
Difference	-	-	-	-7.18%	-	5.47%
Correlation	-	0.9892	-	0.9911	-	0.9859
NRMS Diff.	-	5.63%	-	5.44%	-	2.91%

A scatterplot of the heating and cooling curves with 15% error guides are shown in Figure C-6 and Figure C-7 respectively. During the winter week, RadTherm generally over predicts heating demand for ratings under 1.5kw, but shows good linear correlation just slightly under a 1:1 slope.

In summer, RadTherm consistently predicts lower cooling values, particularly for ratings under 3kw. The boundary conditions for each model are identical, meaning differences could come from RadTherm being a mesh based solver or a difference in the physics calculations. Both possibilities are outside the scope of this study, and the RadTherm BES is considered acceptable.

Figure C-6 – Heater scatterplot comparison for the winter design week

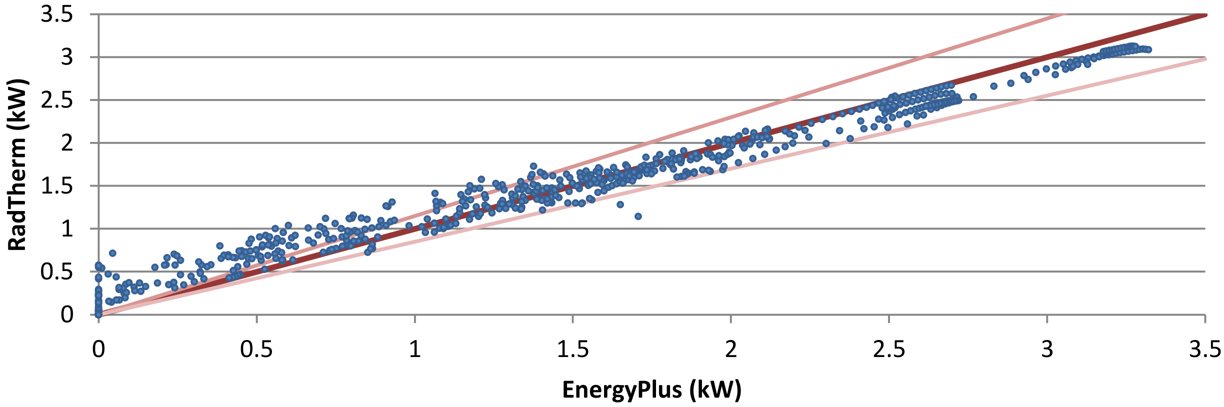
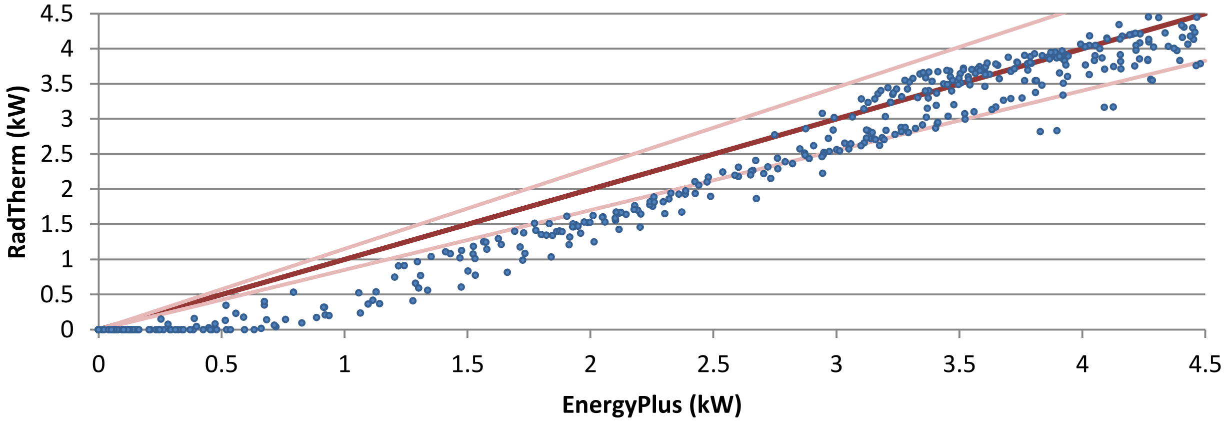


Figure C-7 – Chiller scatterplot comparison for the summer design week



C.5.2 Microclimate Results

The results from the microclimate modeling show a distinct similarity to the single building models. Results from the winter and summer design weeks are in Figure C-8 insert Figure C-9, respectively. In the first stage, the differences between EnergyPlus and RadTherm are nearly the same. When a faceted terrain is added in stage two, both heating and cooling increase in each scene except the summer suburban case. In all cases however, the difference is less than 1.5%. When the microclimate air is added in stage three, heating is increased but cooling is decreased in all scenes except the summer suburban case. For unknown reasons, the suburban scene had unusual results; in EnergyPlus during winter and in RadTherm during summer.

Figure C-8 – Total heating energy for the winter design week microclimate scenes

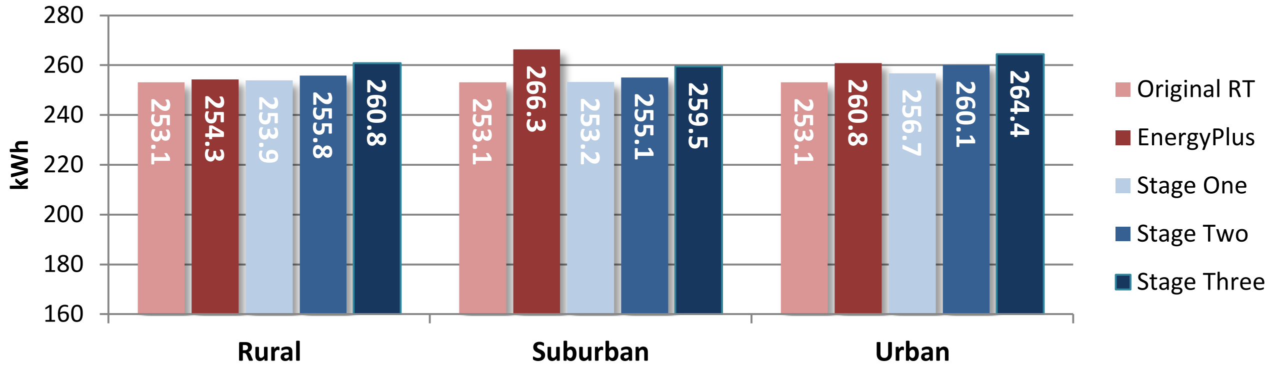
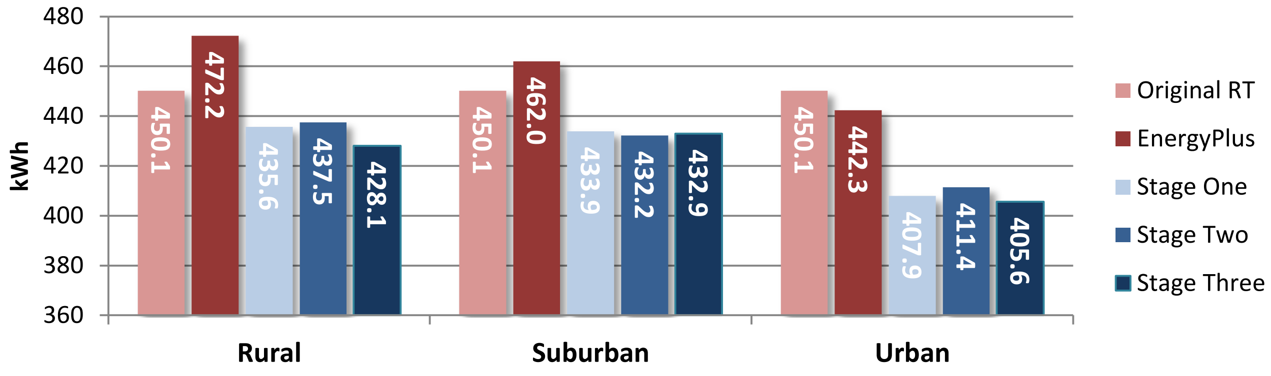
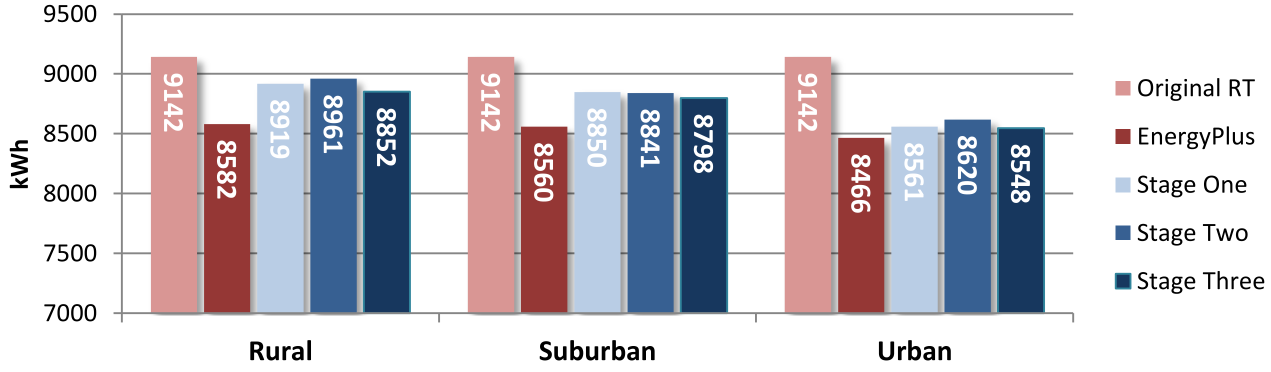


Figure C-9 – Total chilling energy for the winter design week microclimate scenes



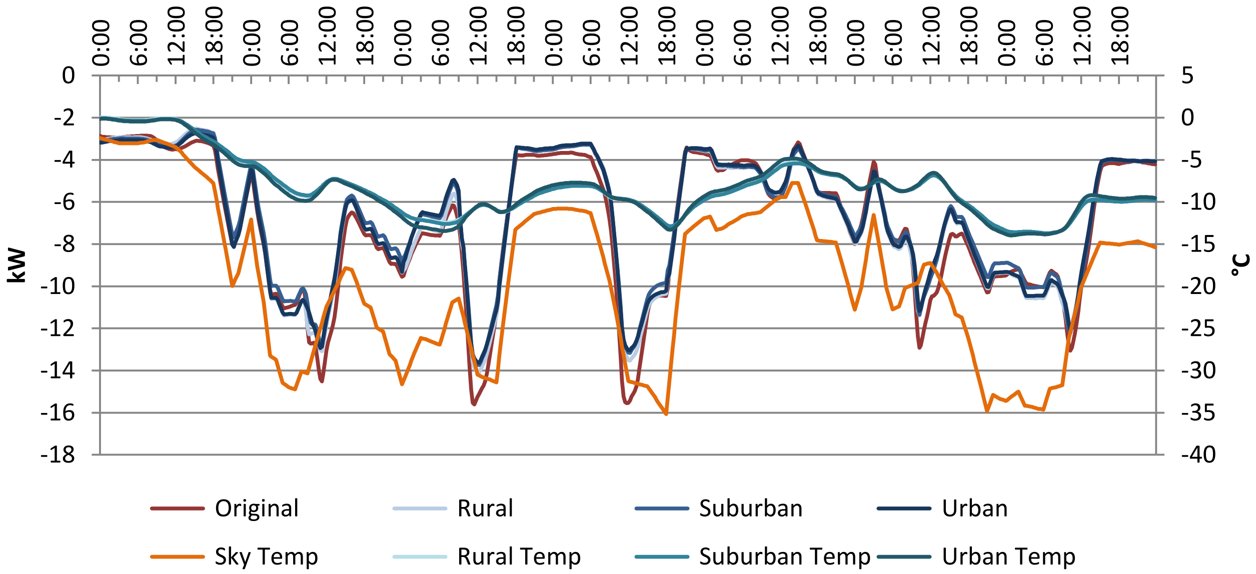
The annual simulations, shown in Figure C-10 below as a sum of heating and cooling, show a significant and unexpected difference. The single building simulations in RadTherm are around 11% higher when heating and cooling are combined; however in every microclimate scene RadTherm less than 4%, and in the urban scene the difference is less than 1%. This is the exact opposite of what would be expected with the heat island effect. Additionally, the difference in energy demands from the original RadTherm building to the no terrain stage are similar to the differences between the other two stages. This lends to the argument that in these types of scenes, shading of direct solar radiation and the appropriate surface properties applied to the background are as critical to capturing microclimatic conditions as calculated surface and local air temperature.

Figure C-10 – Total annual energy for the microclimate scenese



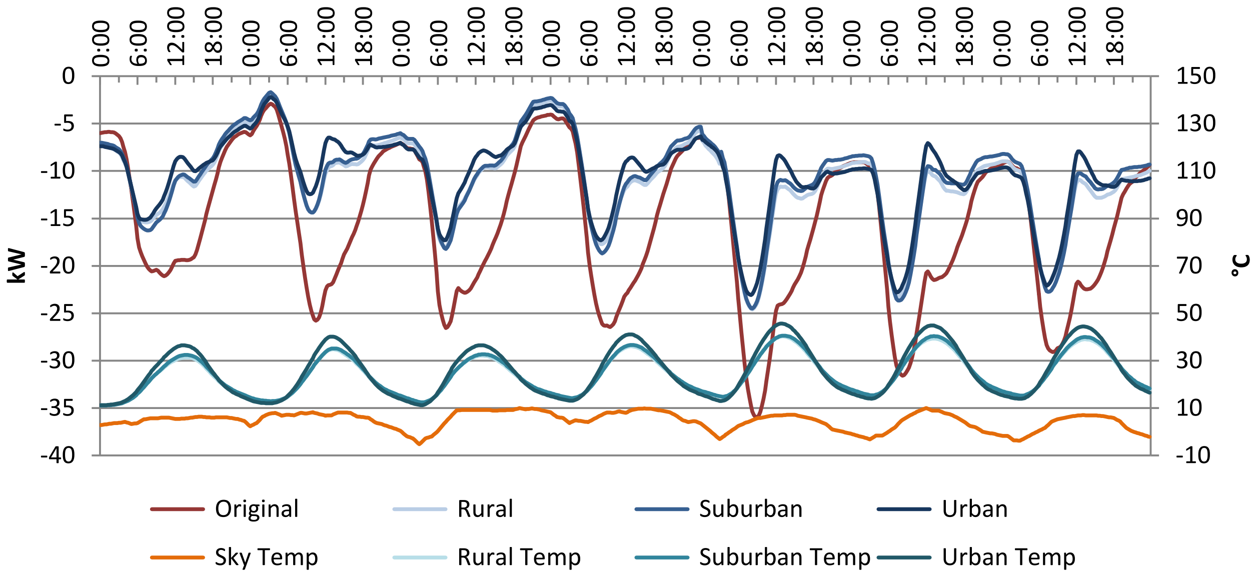
While the energy demand response from within the buildings does not react as expected, the radiant heat transfer occurring outside the building appears to be occurring correctly. With the winter scene having such cold ambient temperatures and little solar radiation, the radiation exchange is largely dominated by the sky temperatures and the radiant heat loss rates are very similar from stage to stage. Radiant heat losses and terrain temperatures for the third stage during the winter week can be seen in Figure C-11 below.

Figure C-11 – Net radiant heat rate with terrain and sky temperatures during winter week



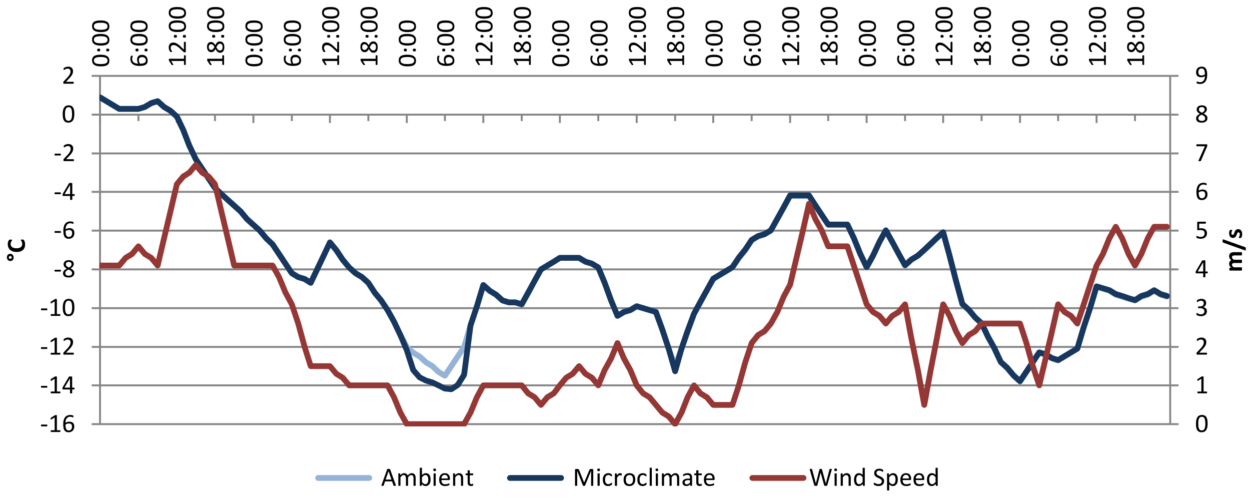
In reviewing the net radiant heat flow in summer, shown in Figure C-12, shows that the modeled terrain can reach temperatures over 20°C higher than the default background. This makes a significant difference in heat rates, with microclimate modeled buildings losing about 30% less radiant heat over the course of the week. Unexpectedly, this does not translate to higher energy demand and the difference between scenes is small. The scene differences may be explained by the lack of water content in the multi-layer soil part, preventing the grass terrain from absorbing more heat and making it more similar to the asphalt terrain model than they may be in actuality. For the energy results, a review of the air nodes is necessary.

Figure C-12 – Net radiant heat rate with terrain and sky temperatures during summer week



In Figure C-13, the results from the urban winter scenes show that the microclimate air nodes are the same temperature as ambient at nearly every time step. The only time there is a deviation is when wind speed is zero, when microclimate temperatures decline 1-2°C. All microclimate air temperatures, both winter and summer, show a strong sensitivity to wind speed. Using a generic wind speed and convection model for the entire scene geometry means the local air node is unable to capture the details in the local wind speeds necessary for this type of microclimate study.

Figure C-13 – Ambient and microclimate air temperatures of urban winter scene with wind speed



A complete overview of the results shows that for the scene geometry used in this study, the assumptions made by EnergyPlus for microclimatic conditions are appropriate. However, in scenes where urban heat island effect will be more prominent, i.e. urban canyon geometry in hotter climates like Madrid or Athens, the changes scene in the radiant heat rate will be more pronounced and may begin to affect the energy demand. Additionally, the use of more common construction without the excessive insulation will aid in demonstrating an energy gain. The microclimate air model does show some potential, but will need refinement, particularly in dramatic geometry such as the urban canyon.

C.6 Conclusions

This study set out to improve the way building energy simulation programs manage the interaction with the local environment which surrounds the target building. To do so, a high powered thermal solver has been sought, RadTherm from ThermoAnalytics, which can handle the radiant and convective interactions with surrounding geometry, as well as model an energy supply system.

The first objective was to establish that RadTherm has the necessary features and tools capable of building energy simulation. The benchmark test results show that RadTherm produces heating and cooling demand curves that over an annual time frame are accurate to within 6%, have a correlation coefficient over 0.98 and have an NRMS of less than 3% when compared to EnergyPlus. These results are within the prescribed acceptance tolerance and establish RadTherm as capable BES software.

Using the qualified BES model, three scenes were created with the target building at the center for the purpose of demonstrating the significance of microclimate on energy demand. The RadTherm model shows a drastic difference in net radiant heat rates of up to 50% when modeling surrounding environmental geometry. The local air temperature model is extremely sensitive to wind, and therefore only shows deviations from ambient air during times of no wind driven air flow.

The annual energy demand has been shown to vary with the added microclimatic features, however total difference is less than 1%. This shows that for the scenes modeled in this study, the simplified assumptions made for long wave radiant exchange in EnergyPlus are reasonable. However, given the documented existence of heat island effect, there are scenes in which these assumptions will not hold. Therefore, a collection of additional work has been suggested, the most significant tasks being;

- Build a new urban AOI that is representative of a more realistic city. This includes buildings which are 6-10 stories high, streets 10m wide, and envelope construction matching common buildings,
- Conduct a CFD study to develop a generic model of wind behavior in dense, urban environments. This work would go into refining the current wind flow and convection coefficient algorithms, and
- Test the terrain part in simulations with the standard wind model to understand the role of moisture in natural terrain.

The changes in energy demand as a result of microclimate demonstrate, even if the scale is small relative to the effects of shading and surface properties, that the basic structure of the RadTherm model is sound. With building geometry built to highlight the heat island effect, RadTherm is expected to calculate a more significant response in energy demand due to radiant gains than what has been presented here. The response could be even greater with development of more appropriate convection algorithms for the urban environment. Ultimately, the modeling procedure presented here is a valuable first step in the design of BES/MC simulations and should be developed further.