Time Step Considerations When Simulating Dynamic Behavior of High-Performance Homes

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ABSTRACT

Building energy simulations, especially those concerning pre-cooling strategies and cooling/heating peak demand management, require careful analysis and detailed understanding of building characteristics. Accurate modeling of the building's thermal response and material properties for thermally massive walls or advanced materials like phase change materials (PCMs) are critically important. However, one input variable that many times is not correctly assessed is time-step dependency. This study is part of an ongoing research effort that has led to the verification and validation of the EnergyPlus PCM and Conduction Finite Difference (CondFD) algorithms in EnergyPlus as well as the simplification of enthalpy linearization for PCMs. This paper demonstrates the importance of using the correct time step depending on the simulation objectives and technology analysed. Using field data of different pre-cooling strategies, this analysis shows and explains the time-step dependency shown in some cases. It also suggests appropriate time-step values depending on the application and HVAC controls.

INTRODUCTION

Residential building air-conditioning and electric heating play a major role in driving peak demand. Together with residential lighting, they can account for up to 40% of total peak load (Koomey and Brown 2002). Thus, a natural place to start addressing peak demand utility challenges is in the residential sector. Researchers have made significant efforts to retrofit houses with energy efficiency measures that focus on utilizing existing thermal mass (distributed thermal storage) or hot water storage (concentrated thermal storage) in residential building along with strategies such as pre-cooling (Xu et al. 2004; Keeney and Braun 1997; Henze et al. 2005; Henze et al. 2007; Sparn et al. 2012). However, using building energy simulations, especially those concerning (1) pre-cooling strategies, (2) cooling/heating peak demand management, and (3) advance envelope assemblies requires careful analysis and detailed understanding of building envelope and load profile characteristics. The analyses of these technologies and strategies are more sensitive to the time step selected than the analyses of energy efficiency technologies that only consider annual energy use. Thus, accurate modeling of the building thermal response and material properties for thermally massive walls or advanced materials like phase-change materials (PCMs) are critically important.

However, one input variable that many times is not correctly assessed is time-step dependency. Time steps are series of discrete bins of time used in time marching algorithms to solve transient problems. In each time step, boundary conditions and dynamic input variables are held constant (EnergyPlus 2012a). Typically, the shorter the time step, the more accurate the solution is at the expense of computational resources and runtime. For this reason, some programs have the capabilities to have variable time steps (Crawley et al. 2005; Sahlin et al. 2005; Sousa 2012).

A previous study analysed different variables that affect the runtime in EnergyPlus, the DOE's building energy simulation program (Hong et al. 2008). Depending on the objective or design stage, the authors recommend time steps from 10 min to 60 min. Their study found important energy differences depending on time step. In addition, EnergyPlus contin-

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uous testing done for every new release is done using different test suites. For building envelope, the tests are ASHRAE 140 (ASHRAE 140 2007) and ASHRAE 1052-RP Toolkit (Rees et al. 2002). In each case, the EnergyPlus developing team uses time steps of 10 and 6, min respectively (Henninger and Witte 2012a; Henninger and Witte 2012b). Other studies have conducted time-step-dependency related research. For example, Cuilla et al. (2010) reviewed some of the previous studies looking at numerical stability of transfer functions and the influence of the time step in conduction heat transfer and thermal inertia. Their studies expressed concern related to reliability of CTFs for walls with high thermal inertia. Dos Santos and Mendes (2004) performed time-step-sensitivity analysis concluding that 1 h time steps can lead to important errors in indoor air temperature and the calculation of conduction loads. However, they also pointed out that linear interpolation of outdoor variables for sub-hourly time steps introduces uncertainty and ended up recommending a 1.5 min time step. Subsequent studies for heat and moisture transfer in soil coupled with a simple lumped building room showed that the results were not very sensitive to time step (Dos Santos and Mendes 2006).

Garde et al. (2001) compared experimental results in a residential house with results using 1 h and 1 min time steps. Overall, their results showed that short time steps can more accurately predict energy consumption for low part-load conditions than hourly time step. Other studies have looked at differential time scale solutions to allow the use of larger time steps for some building component than the building domain time step (e.g., 5 versus 60 min) (Bourgeois and Reinhart 2007). Other nonenvelope inter-program comparative testing for diagnosing errors has used 5 min time steps (Beausoleil-Morrison et al. 2006) and co-simulation studies that have addresses this issue (Treka et al. 2009). Finally, other studies have looked into the effects of the Fourier and Biot numbers on the accuracy of modeling conduction heat transfer in opaque surfaces. In these studies, analytical or experimental data was compared to the results from finite difference algorithms (Pupeikis et al. 2010; Hensen and Nakhi 1994; Waters and Wright 1985).

Among building energy simulation programs, many of them default the time step with 60 min and or use variable time step integration schemes (Crawley et al. 2005). Many users may not change this default time step when running simulations. For example, BEopt, NREL residential building energy optimization software, uses 1 h time steps. However, the impacts of time step on annual, peak, and hourly results as well as optimization procedure have not been fully explored. In fact, the EnergyPlus *Input and Output Reference* considers 1 h as a "long" time step that should only be used sparingly due to problems with accuracy and the introduction of more lag which leads to a dampened dynamic response when compared to a shorter time step (EnergyPlus 2012b). Given the fact that EnergyPlus is generalized building energy simulation software, it is not completely clear how large the impact would be for residential buildings, which are more envelope/weather dependent. Thus, the objective of this study is to analyse and show the importance of using the correct time step when electric peak demand is the key design variable using a simple analytical test and minute average field data. This study is part of a larger project that has an overall goal to improve the accuracy of energy analysis methods for residential buildings (Polly et al. 2011).

TECHNICAL APPROACH

Building Simulation Considerations

This study uses EnergyPlus Version 8.0 to analyse the impact of time step on the dynamic behaviour of high-performance homes. For this particular case, the conduction heat transfer (CTF) algorithm was selected in EnergyPlus from the different conduction heat transfer algorithms. This selection was done as CTFs are the default and most-used conduction heat transfer algorithms in EnergyPlus. CTFs are also very powerful as they relate the current surface heat flux and temperature values to previous surface heat flux and temperature values (ASHRAE 2009). CTFs assume constant thermal properties, thus any simulations for the analysis of PCMs in EnergyPlus need to use the conduction finite difference (CondFD) model. However, the selection of time step with CondFD is limited up to 3 min, avoiding any problems with time-step dependence as shown in previous studies (EnergyPlus 2012a; Tabares-Velasco et al. 2012).

According to the literature, prediction of variables can be reported in two main ways (EnergyPlus 2012a):

- For state variables, such as temperature, wind speed, and heat flux, their predictions are averages over the time step.
- For summed variables, such as heating and/or cooling energy use, their predictions are aggregated totals over the time step.

There are two time steps used in EnergyPlus for calculating the zone temperature: a zone and a system time step. The zone time step is constant and user specified (or default). It is used to update/calculate envelope-related loads and internal loads to the zone. The system time step is variable and can go from one minute up to the zone time step. Zone loads from HVAC system response, infiltration, and air mixing are updated at the system time step.

Users typically have the option to select the reporting frequency or how often a variable will be reported in the output file. This can be as long as the simulation runtime or as short as the selected time step. Because EnergyPlus has two time steps, detailed frequency is used for the system time step and for variables such as cooling energy. In addition, time step frequency is used for the zone time step and for variables such as surface heat flux, surface temperature, or weather data.

Following analytical solutions used in a previous case study to validate EnergyPlus conduction finite difference model (Tabares-Velasco and Griffith 2012), this study initially uses three simple cases that have analytical solutions (wall subjected to sudden constant heat flux change, wall subjected to a step-up temperature boundary condition, wall with a periodic surface temperature), the ASHRAE Standard 140 Case 600 model, and a model of an actual retrofitted house in Sacramento (Booten and Tabares-Velasco 2012). However, this publication will only focus on one of the analytical solutions (wall with a constant heat flux), a retrofitted house, and the same house with higher thermal mass, as the other two analytical solutions did not uncover any additional information concerning conduction heat flux than the heat flux test.

Analytical Solution

This case has a wall with constant heat flux (Carslaw and Jaeger 1986). The wall is made of 5.08 cm (2 in.) of drywall with an initial homogeneous temperature of 26.5°C (80°F). The outside surface is suddenly exposed to a constant heat flux of 150 W/m^2 (47.5 Btu/h·ft^2) while inside surface temperature is kept at 26.5°C (80°F). This problem was selected as it allows the analysis to focus on the conduction heat transfer process through a wall. However, it lacks the actual boundary conditions observed in homes, so extrapolating from it is not suitable.

Retrofitted House Description

The simulated house is an all-electric, 1980s era ranch house located in Sacramento, CA. It has slab-on-grade construction and a total floor area of 161 m^2 (1732 ft^2). The house was retrofitted through the Sacramento Municipal Utility District's (SMUD) deep energy retrofit demonstration program. Figure 1 shows the model implemented in EnergyPlus. The model was originally developed from BEopt but was further expanded in EnergyPlus to allow more customization of the ventilation, wall insulation asymmetry, occupancy schedules, and individual characteristics for items such as ceiling areas (Sparn et al. 2012).

The actual house was instrumented as part of a larger study and the data collected were used to validate hourly simulation predictions (Sparn et al. 2012, Booten and Tabares-Velasco 2012). However, all comparisons done in the previous study were done using 1 h average data in contrast with this study where 1 min data is used. The unoccupied home had simulated occupancy where heaters and lighting was used to simulate occupant's behaviour. Appliance usage was based on the standard occupants assumptions defined in the Building America House Simulation Protocols (Hendron and Engebrecht 2010). Some energy efficiency and renewable energy measures are listed next and more information about the retrofit measures can be found in the literature (Sparn et al. 2012):

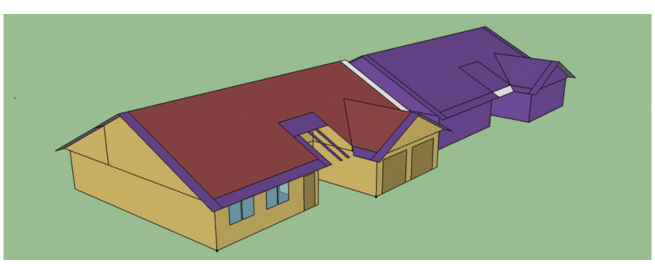


Figure 1 *3D model used in energy simulations.*

1. Attic floor has R-42 blown-in cellulose and the roof has a radiant barrier.
2. Windows were vinyl frame, dual pane Argon filled, low-e with a U-factor = 1.62 W/m^2·K (0.285 Btu/ft^2·h·R) and solar heat gain coefficient (SHGC) = 0.0205.
3. West wall had R-15 blown-in cellulose insulation while the rest of walls had R-11.
4. Blower door infiltration results show an infiltration rate of 3.6 ach @ 50 Pa.
5. A programmable thermostat used to analyse different precooling strategies.
6. House has a heat pump rated at SEER 16/EER 13 HSPF 9.75.

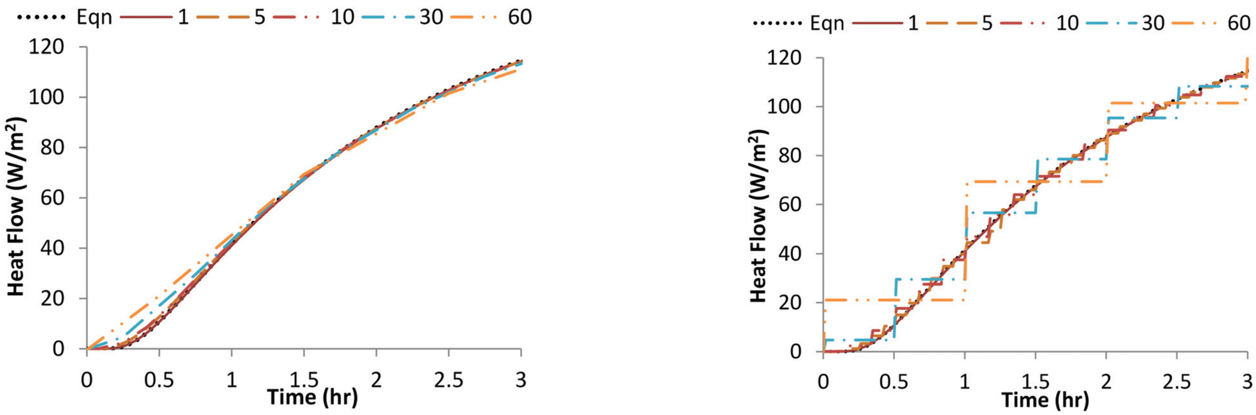
From the different cooling strategies tested during the monitoring period, only one is assessed in this study: a precooling strategy with three different setpoints. This strategy consist in setting the thermostat equal to 21.1°C (70°F) between 10 a.m. and 4 p.m., 26.0°C (79°F) between 4 p.m. and 8 p.m., and 24.1°C (75.4°F) at all other times. The idea of this approach was to provide additional cooling during the morning and early afternoon to attempt to reduce the cooling load during afternoon. It is selected for this study as it had many features that allow the building temperature to float over a couple of hours a day as well as having a drastic indoor air temperature change.

The actual test for the analyzed pre-cooling strategy lasted two weeks. For purposes of eliminating any issues with initial conditions, the house was modeled for several days before the day used for time step analysis to allow for thermal and other transient simulation effects to diminish (Ellis 1998).

RESULTS

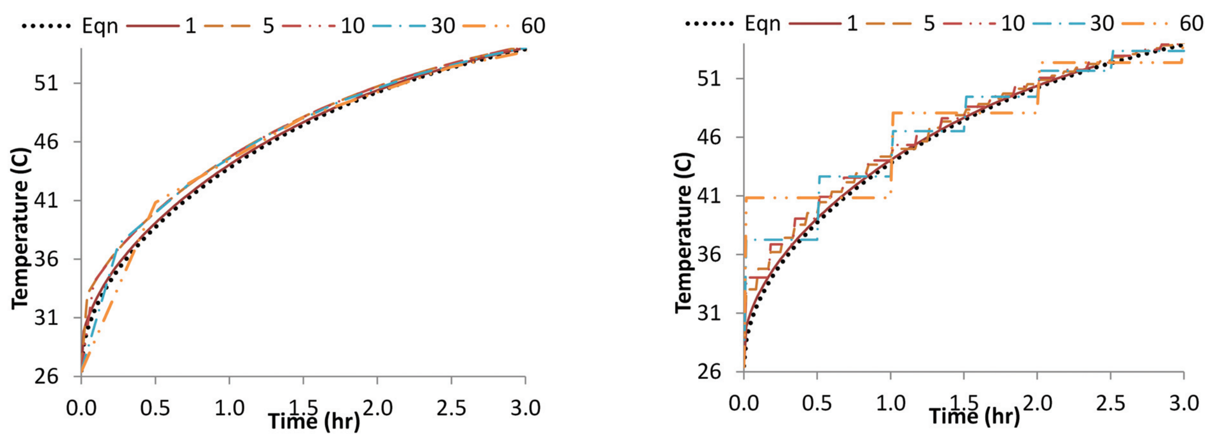
Analytical Solution

Figure 2 shows the exterior surface heat flux. Figure 3 shows predicted temperature of the surface subject to the heat flux. Both figures show the analytical solution (Eqn) and EnergyPlus solutions. Actual analyses considered 1, 5, 10, 15, 20, 30, and 60 min time steps. However, in the following graphs only 1, 5, 30, and 60 min time steps are shown to avoid overcrowding the graphs. Results are reported every zone time step. Figure 2(a) shows the typical scatter plots with straight lines while Figure 2(b) shows the actual discrete/step-up nature of the results. As expressed earlier, EnergyPlus



a. b.

Figure 2 *Exterior surface heat flux for a simple wall subjected to a rapid heat flux. Data shown represents solution for analytical solution (Eqn) and simulation results using multiples times from 1 min time step (1) to 60 min time step (60) for (a) interpolation curve and (b) actual step curve.*



a. b.

Figure 3 *Interior surface temperature for simple wall subjected to a rapid heat flux change.*

reports state variables, such as temperature and heat flux as averages over the time step, thus the need to plot the data as in Figure 2(b) and 3(b).

Figure 2(b) shows that using a 60 min time step totally missed the initial dynamic behaviour of the wall. In fact, only the time steps below 15 react fast enough to catch up with the actual phenomena. However, plotting results with different frequency can be visually misleading as shown in Figure 2(a).

Table 1 shows the results for the first two hours as well as the percentage difference with respect to the analytical solution. The highest differences are observed for the largest time step for the first hour, but tend to decrease with time as it is shown in Figure 3(b) where the 1 h time step overestimates the inner surface temperature and exterior heat flux by about ¾ of the first hour.

The higher difference in the first hour compared to the subsequent ones is mainly due to the slow response of CTFs

Table 1. Average Exterior Surface Heat Flux for the First Two Hours

Time Step	1st hour		2nd hour	
	Average	Difference (%)	Average	Difference (%)
Analytical	14.7		67.1	
1 min	14.6	–1%	66.7	0.6%
5 min	15.5	–7%	66.9	0.3%
10 min	15.6	–8%	66.9	0.2%
15 min	15.9	–10%	67.0	0.0%
20 m	16.2	–12%	67.2	–0.2%
30 min	17.1	–18%	67.6	–0.8%
60 min	21.1	–46%	69.4	–3.4%

and numerical error. The only continuous and smooth curve is the analytical solution, while the simulation solutions are discrete curves that assume average heat flux within a time step (discrete jumps between time steps) as shown in Figure 2(b) and Figure 3(b). Thus the higher differences at larger timesteps are due to a discretization error that is exacerbated at the beginning of the sudden change in the boundary condition problem, when the wall is in equilibrium before being subjected to a heat flux. In other words, during the first hour, the 60 min result overestimated the heat flux about 60% of the first hour, while in the second hour it is overestimated for half of the time but is underpredicted by a similar amount in the second half. Using 1 min time steps have negligible differences with the analytical solution.

As explained earlier, this problem was selected as it has an analytical solution that allows comparison between CTFs and the actual heat flux through the envelope. However, it lacks the typical boundary conditions observed in homes and the temperature values shown in Figure 3 are outside of the typical range for an interior surface, so extrapolating from it is not suitable.

Retrofitted House

Figures 4, 5, and 6 show the cooling electric power, living zone temperature, and the internal loads imposed in the test house. The same nomenclature is used here as in previous figures. Figures 4 and 5 are shown with values reported at the (a) zone time step and (b) system time-step frequency. Using system frequency shows a more rapid response to changes since EneryPlus is using the variable system time step to manage the rapid zone load changes but smaller time steps still show faster response to the dynamic of the house.

Field test data shown are minute averages and are shown for reference only. They are not to necessary determine which time step gets closer to the actual data, as other factors could be affecting the final results of the simulations such as air thermocouple location for the living zone temperature. Figure 4 shows the difference regarding how A/C equipment is typically modeled in BEopt and in other building simulation programs with a part-load ratio (PLR). PLR assumes A/C runs continuously when cooling is needed (from 9 a.m. to 3 p.m. in this example) instead of the on/off cycle that the actual equipment went through.

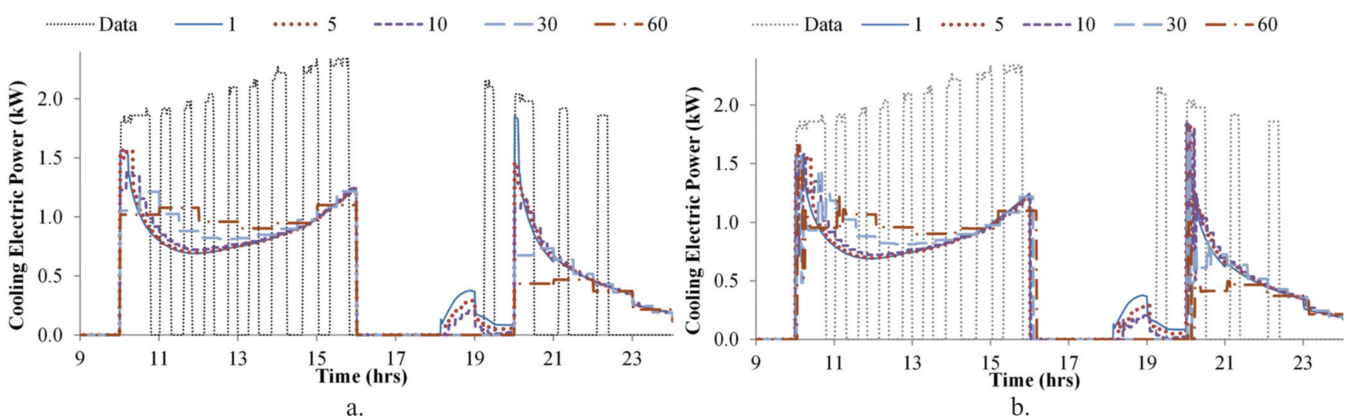


Figure 4 *On-site electric cooling power plotted using (a) time-step frequency and (b) detailed frequency.*

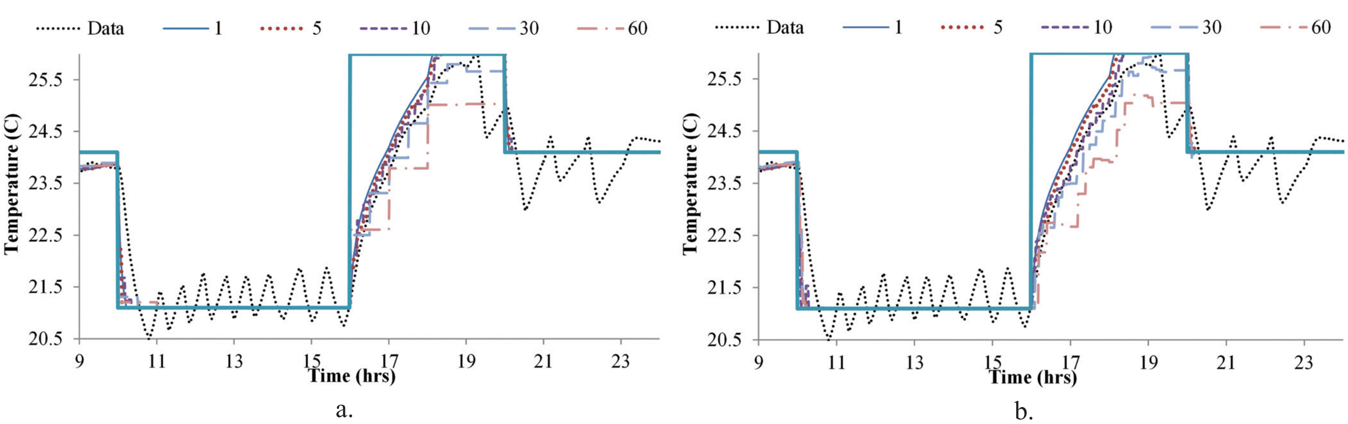


Figure 5 *Living zone air temperature plotted using (a) zone time step frequency and (b) system time-step frequency. (Continuous thick blue line represents thermostat setting.)*

Figure 6 shows the simulated internal loads that were distributed in the house. Location and loads profiles were based on Building America House Simulation Protocols (Hendron and Engebrecht 2010, Sparn et al. 2012). The large internal gain around 18–19 h reflects cooking range among other interior loads that are shifted less than one hour in the simulations with respect with the cooling electric data. This is probably due to perfect mixing assumption in the model for the entire living zone (all bedrooms, kitchen, and living room).

Measured living room temperature in Figure 5 shows how the actual living indoor temperature varies while the A/C is cycling on/off. This effect was not captured in any of the simulations due to part-load ratio assumption used in BEopt. The 30 and 60 min solutions had the slowest response to the setback from 21ºC to 26ºC. In fact the 30 min and 60 min results did not reach the temperature setpoint, while the other solutions with smaller time step did. While in this case living room temperature data shows closer agreement with the 30 min results, actual house temperature varied depending on the location and room: west side rooms were 1–2°C (2–4°F) warmer in the afternoon than the east oriented rooms.

Figure 4 supports the previous statements that larger time steps (20–60 min) tend to damp some of the heat transfer or, at around hour 18, completely ignoring the dynamic thermal behavior of the house. More importantly, the solutions with the larger time steps also underestimate the afternoon peak cooling electric demand. This confirms that using 30 and 60 min time steps tends to underestimate the peak cooling late in the afternoon. Figure 7 shows the same variables as Figure 4 but reporting hourly average cooling electric power instead of every time step. Larger time steps continue underestimating the afternoon peak load even when all solutions are hourly averages. Reporting data hourly as in Figure 7 also tends to underestimate overall peak cooling demand (time = 18–20 h) no matter the time step used and ignore/damps higher frequency thermal behavior of the house. Thus peak cooling load analysis should use time step lower than 60 min (preferably 5 min or lower) and report/output variables with a time step frequency as in Figure 4.

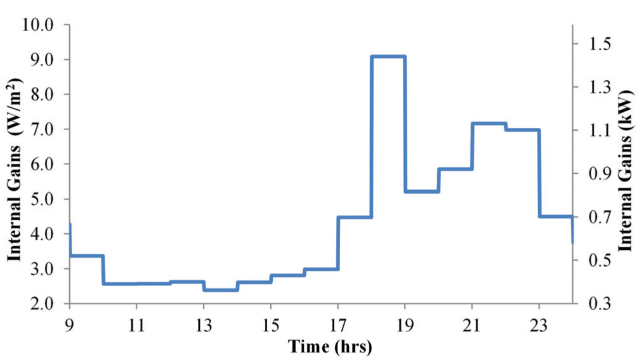


Figure 6 *Total internal heat gains.*

Tables 2 and 3 summarize the results shown in Figure 4 and Figure 7 for the zone and system time step. Time step selection is not critical when daily or longer periods are being analyzed, as the difference between results with different time steps is less than 4%. However, it is very important to report data with system time step when analyzing peak cooling load. Predicted peak cooling load in the afternoon was very sensitive to time step and frequency (zone or system) because of averaging of system time step over the zone time step. For this particular case, reporting values with the zone time step and selecting a 60 min time step can underestimate the afternoon cooling peak demand by 75%. Using the system time step will underestimate the afternoon cooling peak demand by 46%. It is only when results are reported using system time step with time steps lower than 10 min that results are close to the measured afternoon cooling peak demand.

Figure 8 shows the interior surface heat flux for the south wall. This figure is only shown in zone time step since EnergyPlus keeps surface temperature and calculated heat fluxes constant during the time step. Notice in Figure 8 how the larger time steps lead to lag in the heat transfer between the air and the wall. In the late afternoon, larger time steps also completely missed the dynamic behaviour of the wall reacting to the change in setpoints and increase in internal loads. Unfortunately, no heat flux data was measured in any wall in the house.

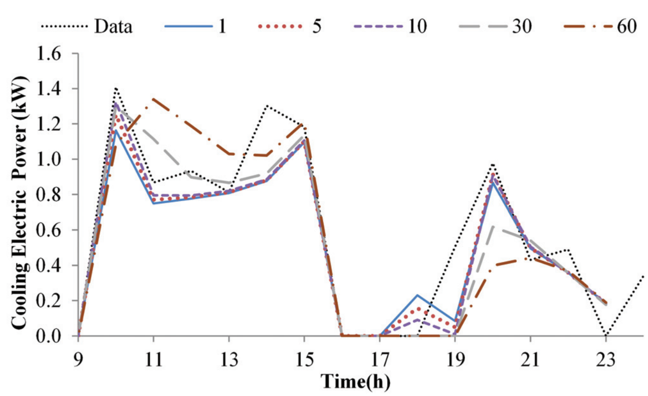


Figure 7 *On-site electric cooling power, hourly output.*

Table 2. On-Site Cooling Energy Use and Afternoon Peak Demand Using Zone Time Step

Time Step	Data	1 min	5 min	10 min	15 min	20 min	30 min	60 min
24 h Cooling Energy (kWh)	9.56	8.08	8.02	8.00	7.98	8.01	7.96	7.78
Difference (%)			0.8	0.9	1.1	0.8	1.5	3.6
Afternoon Peak Load (kW)	2.2	1.8	1.5	1.1	1.0	0.9	0.7	0.5
Difference (%)			21	39	46	51	61	75

Figure 9 shows the slab interior heat fluxes. For this variable, two heat flux meters were installed in a bedroom closet under the carpet. There is a large variation in the heat flux in the afternoon due to both the change in setpoint and the solar gain. There are also shorter oscillations due to the on/off A/C cycling. As with other figures, field data is shown only as a reference, as in this case two heat flux meters are not representative of the entire slab heat transfer which is calculated by the model. However, all simulations follow the same trend as the field data, but the heat flux magnitudes are shifted.

Both Figure 8 and Figure 9 show how larger time steps affect the heat flux and lead to an overall lag in the heat transfer between the slab/wall and the indoor air. In particular, the predicted heat flux from the south wall using larger time steps completely misses the afternoon peak. Floor and south wall heat flux peaks in the afternoon can be underestimated by more than 50% for cases with an hourly time step.

Figure 10 shows the total internal convective heat gain rate (kW) for the living zone. This figure also explains the differences observed previously in cooling energy use. Calculated south wall convection coefficients are not shown here, due to space limitations but for this particular afternoon and precooling strategy, the south wall convection coefficient changed from 1.2 to 3.5 $W/m^2 \cdot K$ ($0.21–0.62$ $Btu/h \cdot ft^2 \cdot R$) for the 1 min time step while the 60 min solution only varies from 1.2 to 2 $W/m^2 \cdot K$ ($0.21–0.35$ $Btu/h \cdot ft^2 \cdot R$) with a two hour delay in which the heat transfer coefficient changes. This further explains the slow response seen in the 60 min solution in Figure 8.

Finally, to fully understand the impact of time step, Figure 11 shows the interior surface temperature for the south wall. Unfortunately, wall surface temperatures were not measured either, thus there is no data to compare. The difference between the 1 min and 60 min solutions for the floor and south wall can be as large as 2°C (4°F).

Table 3. On-site Cooling Energy Use and Afternoon Peak Demand Using System Time Step

Time Step	Data	1 min	5 min	10 min	15 min	20 min	30 min	60 min
24 h Cooling Energy (kWh)	9.56	8.08	8.02	8.00	7.98	8.01	7.96	7.78
Difference (%)			0.8	0.9	1.1	0.8	1.5	3.6
Afternoon Peak Load (kW)	2.2	1.85	1.85	1.83	1.81	1.8	1.76	1
Difference (%)			0.3	1	2.5	2.7	4.8	46

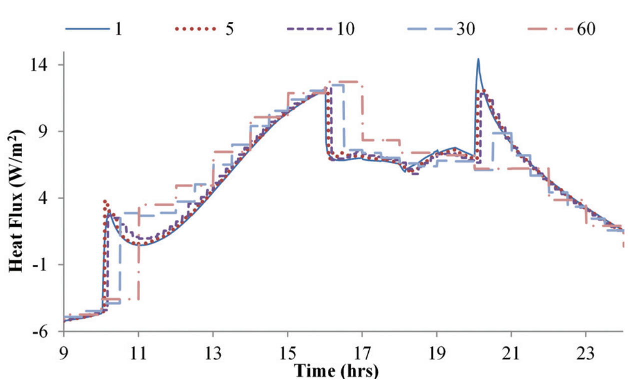


Figure 8 *Interior surface heat flux for south wall.*

Retrofitted House with High Thermal Mass

The same retrofitted house was analysed but in a scenario where the internal thermal mass is increased by using PCMs or installing large furniture. This was done by increasing the thickness of the drywall from 0.013 m (½ in.) to 0.10 m (4 in.). Figure 12 shows the cooling electric power for the retrofitted house (light) and high thermal mass (heavy) using a 1 and 60 min time step reported with the system time step. Morning cooling load increase and thermal behaviour is

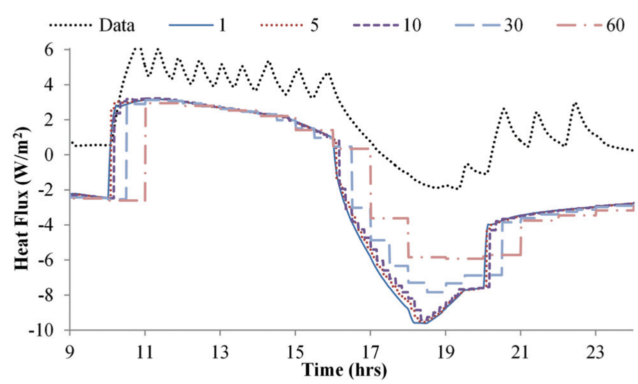


Figure 9 *Slab interior heat flux.*

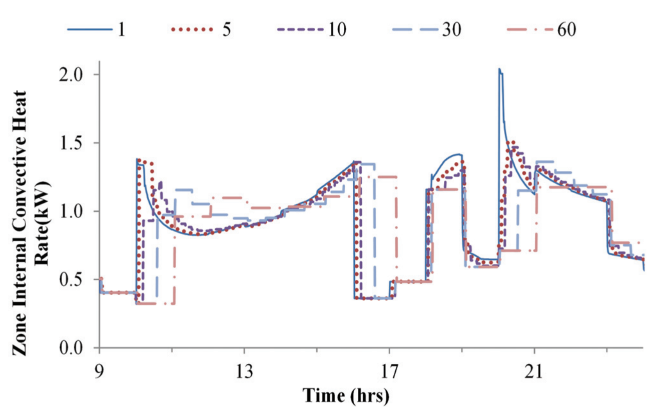


Figure 10 *Zone Internal convective heat gain rate calculated with system time step.*

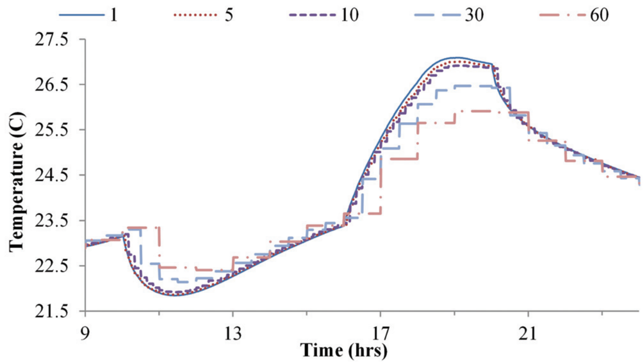


Figure 11 *South wall interior surface temperature.*

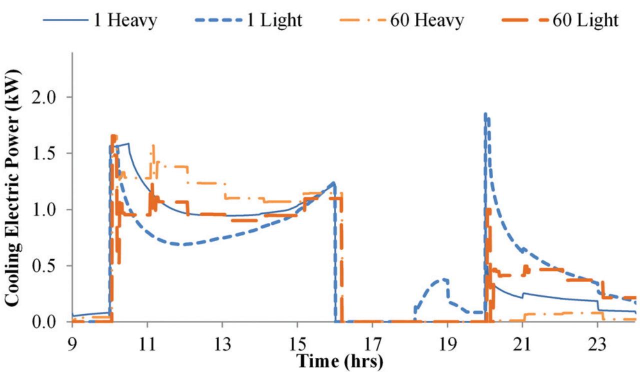


Figure 12 *On-site electric cooling power for a light and heavy retrofitted house calculated with 1 and 60 min time step.*

well predicted with both time steps due to the added thermal mass that needs to cool down. However, the 60 min time steps oscillates slightly at 10 a.m. when the A/C starts running. The most important differences are in the afternoon, the 60 min model predicts almost zero cooling energy use for the high thermal mass, while the 1 min time step does not, with a short spike, and an almost constant load of 0.4 kW. More important, this example shows that users should always compare technologies or designs using the same time step.

DISCUSSION FROM TIME STEP ANALYSIS

Results presented here show that if peak air-conditioning load is an important factor to consider, users should use time step of 10 min or less using the system time-step frequency. This will ensure that all important transient phenomena are well calculated at the expense of increased runtime. The same recommendation might apply when TOU rates are used. However, if the interest of a study is only annual energy consumption, then users can freely select hourly simulations to speed up the results. The time-step selection is an important variable to consider since it affects all heat transfer processes in the building whenever fast changes take place inside the building due to HVAC controls (set back) or internal gains profiles as shown in this study. Missing this dynamic behaviour of the building can ultimately lead to incorrect predictions of the cooling load. This conclusion is consistent with results found in Garde et al. (2001) and Dos Santos and Mendes (2004) that suggest time steps of only a few minutes. Although not explored here, this preliminary research also agrees with Cuilla et al. (2010) that weather data interpolation for subhourly values impacts the subhourly results, but a definitive conclusion requires further analysis. For this particular case, the runtime for the 1 min time step was 5 min, while the runtime for the 60 min case was 37 s. The runtime difference between 60 and 1 min cases is a factor of around 8.

CONCLUSIONS

Building energy simulations, especially those concerning pre-cooling strategies and cooling/heating peak demand management, require careful analysis and detailed understanding of building characteristics. Depending on the simulation objectives and technology analysed, this paper shows the importance of using the correct time step and reporting frequency (when variable time steps are allowed). By examining a simple case with an analytical solution and field data from a lab home using a pre-cooling strategy this study shows and explains the time-step dependency of building energy simulations with rapid temperature oscillations. Overall, this study found that for these particular cases, users should use time-steps lower than 10 min to ensure the thermal dynamic behaviour of residential buildings are fully modeled for peak load scenarios. The results for this particular pre-cooling strategy showed that using a 60 min time step could underestimate the peak load up to 70%. However, if annual energy consumption is the main interest, users can use larger time steps.

ACKNOWLEDGMENTS

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