DIFFERENTIAL TIME SCALE SOLUTIONS FOR DYNAMIC BOUNDARY CONDITIONS WITHIN WHOLE-BUILDING ENERGY SIMULATION

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ABSTRACT

This paper presents a set of solutions to enable differential time scales for dynamic boundary conditions within whole-building energy simulation, specifically occupant behavioral adaptations in response to short-term changes in solar and daylighting conditions. The concept is to allow specialized libraries to determine in tandem the state of critical variables, such as window blinds and lighting systems, at higher frequencies than the building domain time step (e.g. 5 versus 60 minutes), and in turn set critical building domain boundary conditions, aggregated over the time step period (e.g. aggregated lighting loads over 60 minutes). The hypothesis is that the strategy would provide substantial savings in simulation time, in principle without penalizing simulation accuracy. Experiments were carried out on single-occupancy and open plan offices, and classrooms, with building domain simulation time steps ranging from 5 to 60 minutes, while allowing specialized libraries to set in conjunction solar and daylighting values and component states at 5 minute intervals. Relative discrepancies were more strongly found for heating loads in single-occupancy offices, yet remained under 5% in all cases. Relative discrepancies in peak cooling demand in open-plan office environments approached 2%. Relative discrepancies for cooling loads and peak heating loads were all under 1% in all cases. Results clearly support the premise that substantial gains in simulation time are possible this way without penalizing simulation accuracy.

KEYWORDS

daylighting, energy, occupant behavioral response, Daylight 1-2-3, SHOCC, DDS, Radiance, ESP-r

INTRODUCTION

Time constants of many building structures are often adequately approximated at an hour, yet certain phenomena should ideally be simulated at much higher frequencies to yield meaningful results. Energy simulation programs like ESP-r and Energy Plus already provide functionality to process plant systems at higher frequencies than building fabric. A similar set of examples includes sub-hourly variations of meteorological conditions (e.g. sky conditions, wind turbulence) and subsequent occupant behavioral adaptations (e.g. lowering venetian blinds in response to glare, closing operable windows as a function of indoor air velocities). In existing simulation programs, taking into account such short-term changes in boundary conditions has meant imposing unnecessarily high simulation frequencies for the thermal response of building structures.

The paper investigates the benefits of setting external boundary conditions at higher frequencies that the building domain in energy simulation, specifically occupant behavioral adaptations in response to dynamic solar and daylighting conditions. The paper focuses mainly on two dialoguing software libraries, SHOCC and DDS, integrated within ESP-r. DDS is used to accurately predict solar and daylighting quantities, while SHOCC provides short-term occupant behavioral responses. The concept of the differential time scale solution is to allow specialized libraries to determine in tandem the state of critical variables, such as window blinds and lighting systems, at higher frequencies than the building domain time step (e.g. 5 versus 60 minutes), and in turn return critical building domain boundary conditions, aggregated over the time step period (e.g. aggregated lighting loads over 60 minutes). The hypothesis is that the solution would provide substantial savings in simulation time, in principle without penalizing simulation accuracy.

CONTEXT

Daylight 1-2-3

The presented work was developed within the context of Daylight 1-2-3, a new daylighting/energy analysis software for design professionals and architectural students with an interest in daylighting and sustainable design, but without previous knowledge of either daylighting concepts or simulations. As described more thoroughly in Reinhart et al. (2007), the objective was to offer to a wide audience an easy-to-use, yet accurate, reliable and *fast* tool to assess the quality - and overall energy use - of daylighting solutions in office and classroom environments. The developed solution is one that relies on an intuitive client-side 3D graphical user interface (GUI) allowing users to easily describe their project within a few minutes, and as a second step on a powerful server-side back-engine that provides a fully-integrated annual lighting/thermal simulation. The back-engine couples Radiance-based (Ward Larson & Shakespeare) daylight coefficients using a specialized software library called DDS (Bourgeois et al. 2007), optical and thermal data using SkyVision correction factors for windows (w/o venetian blinds) and skylights (Laouadi et al. 2007), and occupant behavioral models using another specialized software library called SHOCC (Bourgeois et al. 2006), all within the whole-building energy simulation engine ESP-r (ESRU 2007). At the end of each simulation, the server-side back-engine returns various outputs back to the client-side GUI, which are presented as intuitive false-color maps of annual daylighting performance metrics, e.g. daylight autonomies, useful daylight illuminances (Reinhart et al. 2006, Nabil & Mardaljevic 2005), and monthly histograms of lighting, heating and cooling energy requirements.

Reducing run-times

One of the targets for Daylight 1-2-3 was that the entire process from the user description of a project using the 3D GUI to final visualization of annual performance metrics would only take a few minutes so that the tool could easily be used within the context of an initial design meeting. Once all inputs defined, the overall targeted simulation duration - from the moment a user initiates a simulation by pressing the GUI *RUN* button to the final visualization of results - was set approximately at a single minute, a time lapse beyond which the development team no longer considered the tool as *fast*.

A number of simple and obvious choices were made to keep simulation times as low as possible, such as only monitoring variables and reporting results which were strictly useful for Daylight 1-2-3 users, as well as streamlining communications between client- and server-side processes. However, these efforts were insufficient to achieve the desired goal. One of the remaining bottlenecks in the process remained the chosen simulation time-step duration.

To yield meaningful results which are consistent with the nature of some of the investigated controls in Daylight 1-2-3, such as occupancy-sensing and manual switching of lighting fixtures, sub-hourly simulation intervals are recommended, generally in the order of 5 minutes (Reinhart 2004). Other than the behavioral response and mobility of occupants, there are no key variables in the Daylight 1-2-3 ESP-r-based back-engine that require such short simulation time-steps, the simulated rooms not being equipped with explicit electrical or mechanical systems or plant. A simulation time-step of one hour was hypothesized to be adequate for simulating the thermal response of building fabric, and would render the 1-minute target viable.

DIFFERENTIAL TIME SOLUTION

The proposed solution to achieve the simulation time target was to allow both specialized libraries, SHOCC and DDS, to carry out their internal computations at 5 minute intervals to simulate short-term occupant behavioral response to daylighting quantities, while reporting aggregated or averaged *states* (e.g. control states, casual gains) necessary for ESP-r energy calculation at hourly frequencies. A brief overview of how DDS and SHOCC interact within - and with - ESP-r is first presented before describing the proposed differential time scale solution.

Normally at every building simulation time step and for each thermal zone, the ESP-r simulator sequentially updates boundary conditions for each technical domain, computes new domain solutions, and moves on to solve the next domain equations, often sending the preceding solutions as boundary conditions for the next set of domain equations to solve. The time flow of a typical ESP-r simulation is schematically represented in Figure 1.

Pertaining to daylighting control, the status of each transparent surface (i.e. blinds open/drawn) is determined during the solar calculations; which becomes input for natural illuminance calculations, required to set lighting output during casual gain computations. Data is passed from one domain to another by directly accessing global data structures. This process is repeated until the end of the simulation.

The main challenge in enabling differential time scales with respect to dynamic boundary conditions and building fabric is that the vast majority of these boundary conditions are dynamically set within the thermal zone loop, which is itself embedded within the various temporal loops. As such, it is essentially impossible to introduce temporal frequencies in setting boundary conditions greater than those of building fabric without having to go through all zone-specific plus technical-domain-specific calculations, thus defeating the initial objective of saving simulation time. A second issue, although not as critical in the case of Daylight 1-2-3 simulations, arises from the fact that boundary conditions are treated as to influence each thermal zone in relative isolation to one another. In real life situations, external boundary conditions such as daylighting or solar exposure can influence environmental variables in *non-perimeter* zones, though initially passing through *perimeter* zones. Examples include daylighting via atria or through multiple skin facades. The sudden behavioral adaptation to direct glare from daylighting in one zone, such as lowering blinds for instance, can significantly alter daylighting conditions in other zones. Such conditions are not investigated *per se* in the Daylight-1-2-3 tool, but the basic functionality to do so was taken into consideration for generalized use by ESP-r users in the future.

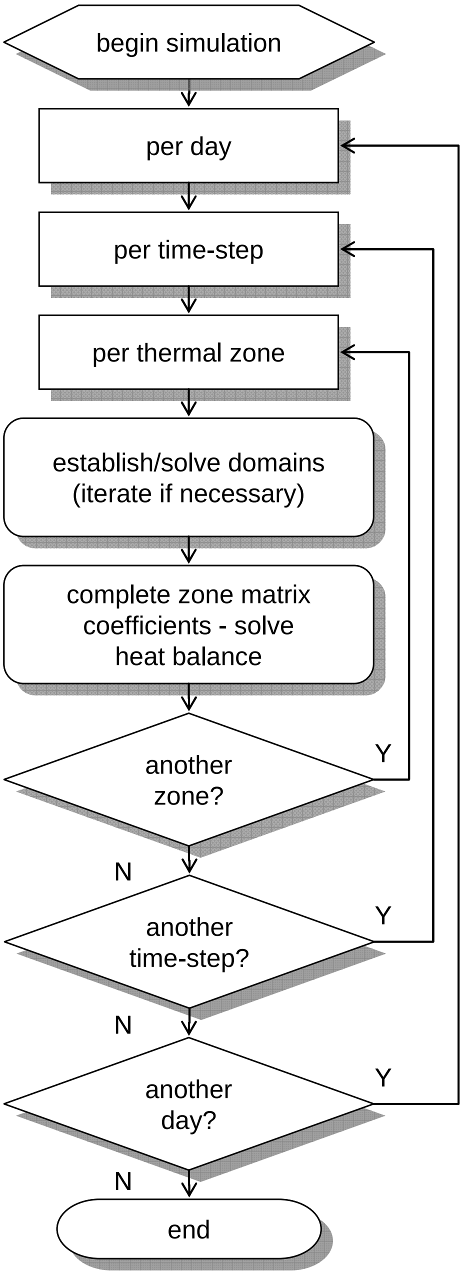

Figure 1 Time flow schematic of an ESP-r simulation

The proposed solution, illustrated in Figure 2, is a two-step process whereby the required external boundary conditions are first dynamically set and stored in memory at higher frequencies than the building time step before looping within each thermal zone, and then, as a second step, are subsequently retrieved from memory, aggregated or averaged over the building time step duration and used to update targeted domain variables.

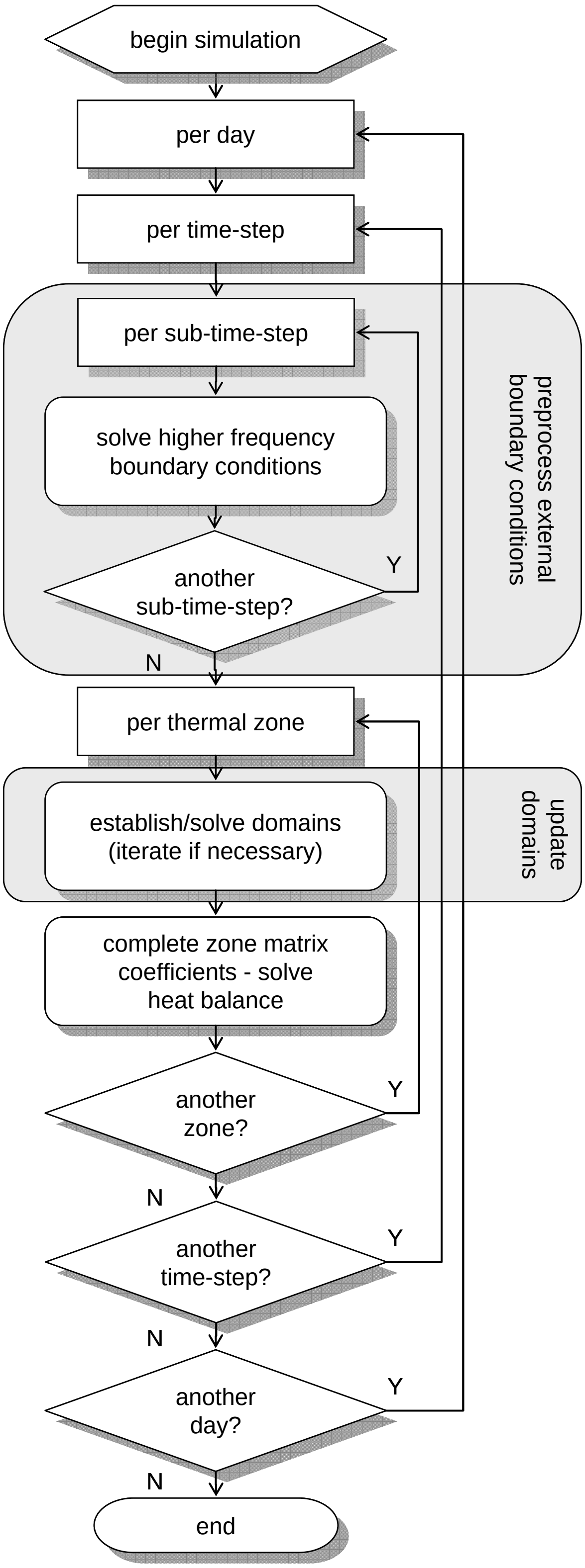

Figure 2 Time flow schematic of an ESP-r simulation enabling a differential time scale solution

The first step requires that ESP-r initially updates key environmental boundary conditions, such as solar data and meteorological conditions, which are then passed as input to preprocessing external boundary conditions as a result of a *dialogue* between DDS and

SHOCC, implemented within a sub-time step loop as shown in Figure 2. There are several possible outcomes given occupancy and behavioral characteristics, meteorological conditions, building design, etc. but the following example *dialogue* gives a clue as to some of the possibilities:

1. DDS receives meteorological conditions and internally calculates solar characteristics and sky luminance distribution, and subsequently daylighting and solar quantities at defined sensor points throughout the building.
2. SHOCC queries DDS to identify new glare conditions which might trigger window blind occlusion, as long as individuals that *own* control over window blinds are present.
3. DDS considers if blind occlusion takes place and brings necessary changes to daylighting and solar quantities at defined sensor points.
4. SHOCC again queries DDS to update other sensed boundary conditions, such as the minimum illuminance among a cluster of sensor points in a room, which can trigger the manual switching of electric lighting systems or modulate a photocell-controlled dimming system.

The technical means by which these two dialoguing libraries effectively communicate such critical information will not be described further in this paper. More detailed descriptions are provided in Bourgeois et al. (2006, 2007). Suffice to state here that critical information resulting from these processes, such as the short term state of electrical lighting systems, are kept in memory for further use, i.e. within the zone-specific technical domain solutions.

Once the short term states (i.e. over all sub-time steps) of all critical parameters are obtained and stored in memory within either DDS or SHOCC libraries, the ESP-r time manager moves forward and loops to solve each zone's technical domain solutions, e.g. solar and casual gains, airflow. It is at these critical steps when SHOCC – mainly - aggregates or averages – depending on the nature of the controlled device – the sub-time varying states of each device, such as the aggregated heat output of a lighting system, and updates the matching ESP-r casual gain for its own energy balance calculations.

The proposed solution offers the advantage that the complex interactions between external boundary conditions, building and occupants can be simulated at time intervals that are considered suitable (e.g. 5 minutes), while reducing overall simulation time by choosing much longer building time steps (e.g. 1 hour). The following simulation experiment was undertaken to investigate the impact of increasing building time step duration from 5 to 60 minutes on simulation accuracy.

Influence of time step duration on accuracy

To investigate the extent of possible simulation errors due to increasing building time step length, and thus shorter overall simulation duration, three Daylight 1-2-3 room types were chosen for demonstration purposes: a single-occupancy cellular office, shown in Figure 4; an open plan office environment, shown in Figure 5; and a classroom, shown in Figure 6. In all three figures, *continuous daylight autonomy* distributions are illustrated; a function of room dimensions and material properties, site location (Beijing), and occupant-control over window blinds.

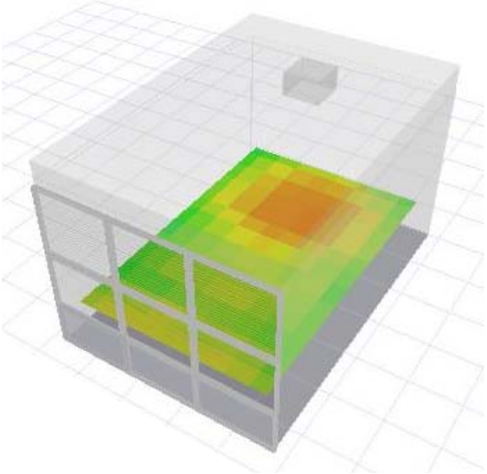

Figure 4 Cellular office showing continuous daylight autonomy distribution

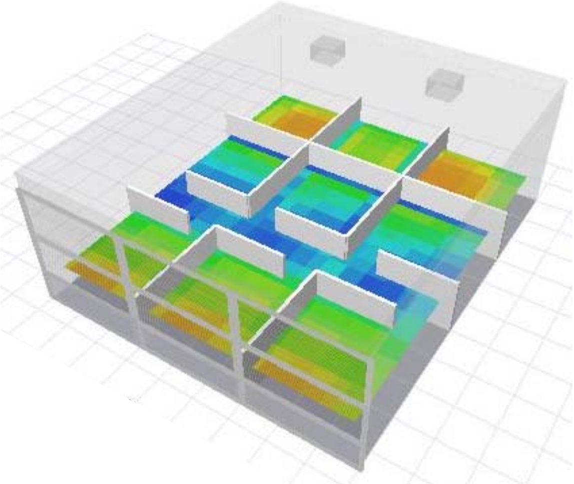

Figure 5 Open plan office environment showing continuous daylight autonomy distribution

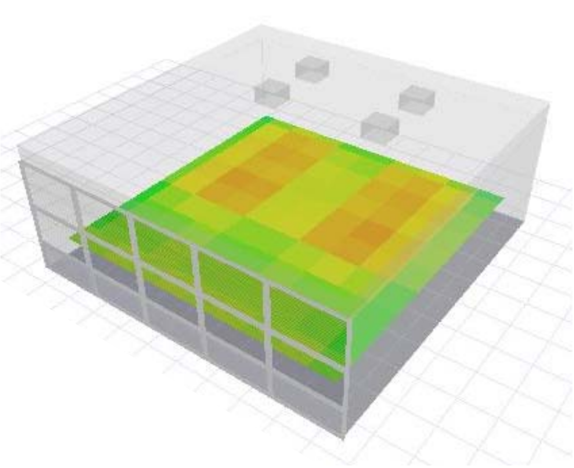

Figure 6 Classroom showing continuous daylight autonomy distribution

In all cases, the glazed façade is oriented south-west; all other surfaces except the roof are considered to be in an adiabatic state with neighboring rooms. The building thermal mass is considered as being *heavy* and external opaque wall, glazed curtain wall and roof are assumed to comply to very high thermal insulation standards (i.e. complying to most energy standards in Canada).

All window blinds and lighting systems are manually controlled. Lighting systems are equipped with photocell dimming controls to ideally meet 500 lux. Occupancy sensors are also introduced to switch off lighting fixtures when either workstations (for the open plan office) or entire rooms (for single occupancy offices or classrooms) are left unattended beyond 5 minutes. Lighting power density in all cases is assumed to be 15 W/m2. All simulated occupants in the rooms are assumed to be using laptops that they take with them at the end of the day. The cellular office is occupied by a single occupant, while all nine workstations in the open plan office environment are occupied by individual workers. The classroom is occupied by a teacher and 30 students. Typical 9-to-5 schedules are defined for office environments, while usual morning-to-mid-afternoon schedules are defined for the classroom. Stochastic variations of individual mobility patterns are simulated, which provides more realism.

Annual heating and cooling requirements, as well as annual peak heating and cooling demand, were calculated for various building time step durations, while running the DDS + SHOCC preprocessing of external boundary conditions at 5 minutes for all cases. Building time step duration varied from more accurate (5 minutes) to less accurate (1 hour). Obviously, the desired goal would be that the 1 hour building simulation time step would not generate significant simulation discrepancies.

Directly comparing simulation times between cases is not a straightforward exercise. Reading in input files and writing out results is often a time consuming process in any energy simulation program and should be considered as a constant penalty in all cases; it is not by increasing building simulation time step duration that reading in input files will take any less longer.

Additionally, some cases require more DDS + SHOCC interaction than others. For instance, open plan office environments are defined with a denser grid of DDS daylight sensors than in other room types; this has a significant influence on overall simulation time. Similarly, SHOCC only simulates one occupant in the cellular offices, while simulating 30 students in classrooms.

Rather than measuring actual simulation times (e.g. using the UNIX *time* utility), relative discrepancies in simulation results in comparison to the most accurate case (at 5 minutes) are shown against 10, 15, 30 and 60 minute building time step duration, as illustrated in Figures 7 to 10. All figures use a relative discrepancy scale (Y-axis) of 5% to facilitate visual analysis.

Results

Figure 7 shows the relative discrepancies in annual heating requirements in comparison to the most accurate case. In all cases, annual heating requirements systematically increase with greater building time step duration. This is especially notable in room types that have greater heating requirements, such as the cellular office, which reaches nearly 5%.

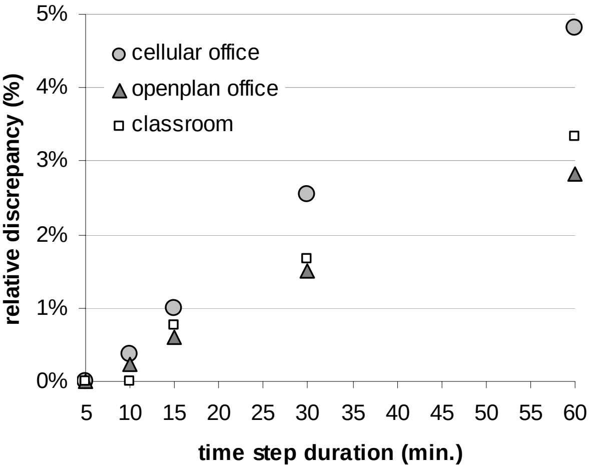

Figure 7 Relative discrepancies of annual heating requirements (e.g. kWh) for the investigated rooms. Annual heating requirement systematically increase with greater building time step duration

The general trend can be attributed to the fact that DDS and SHOCC simulate high frequency changes in solar loads and electric casual gain loads in each environment, which can strongly influence room air temperatures before being stored in the building fabric. If a lighting system is suddenly switched on for instance, then the instantaneous heat injection in the room can quickly increase room air temperatures, whereas the traditional approach of using hourly diversity profiles to describe lighting output, regardless of whether the building time step duration is actually one hour or 5 minutes, tends to smooth out such sudden shifts by aggregating data over an hour. This latter approach increases the likelihood of having room air temperatures ideally matching heating setpoint temperatures. Of all the investigated metrics, annual heating requirements are the most susceptible to increases in building time step duration. This should be considered carefully when simulating building response to heating-dominant climatic conditions, or for building or room typologies that require considerable heating.

Figure 8 shows the relative discrepancies in annual cooling requirements. Contrary to the annual heating requirements, the impact of increasing building time step duration is not as strongly felt, never exceeding 1%. This appears attributable to the strong influence of the heavy thermal mass in response to – mainly – climate-based cooling requirements, given the low internal load characteristics of the investigated typologies. Note that the classroom is barely occupied during summers.

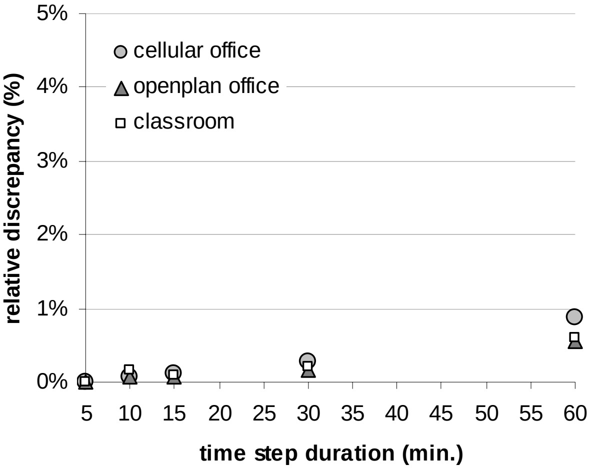

Figure 8 Relative discrepancies of annual cooling requirements (e.g. kWh) for the investigated rooms. Annual cooling requirement systematically decrease with greater building time step duration.

Figure 9 illustrates the relative discrepancies in annual peak heating demand. Not surprisingly, building time step duration has little influence over peak heating demand as this usually corresponds to periods of prolonged absenteeism (e.g. cold weekends).

Figure 10 shows the relative discrepancies in annual peak cooling demand. Here, differences are negligible for the classroom (which is essentially vacant during the main cooling period) and is almost negligible for the cellular office (which has little internal heat gain to create any significant cooling load).

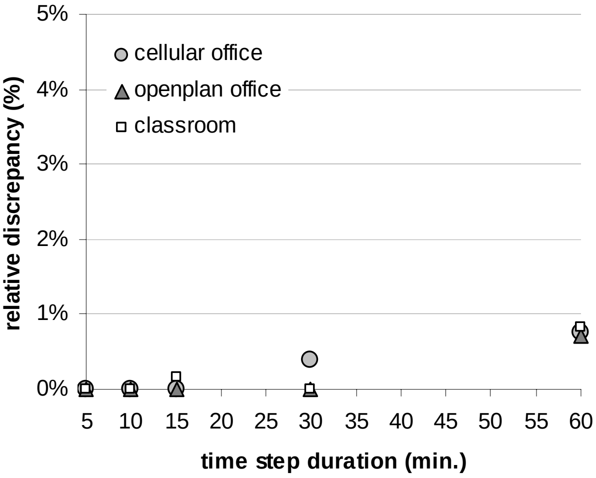

Figure 9 Relative discrepancies of annual peak heating demand (e.g. kW) for the investigated rooms. Annual peak heating demand systematically increases with greater building time step duration.

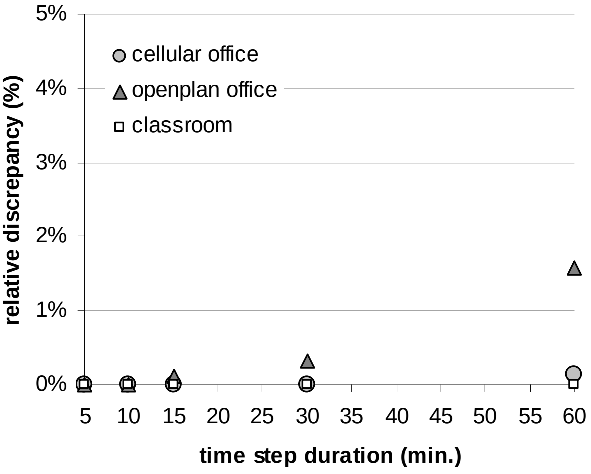

Figure 10 Relative discrepancies of annual peak heating demand (e.g. kW) for the investigated rooms. Annual peak heating demand systematically increases with greater building time step duration.

Differences are more noticeable for the open plan office environment, likely because this room type has the greatest chance of having coincident summer meteorological conditions and internal gains that set the annual peak cooling demand. Again, SHOCC and DDS simulate short-term changes that increase the likelihood of creating strong peak demand, rather than relying on the traditional diversity factors which tend to smooth out energy demand over an hour.

In summary, results suggest that increasing the building simulation time step to one hour, while allowing DDS + SHOCC to operate at 5 minute intervals to preprocess external boundary conditions is achievable with relative discrepancies under 5% in heating requirement estimations and under 2% for annual peak demand estimations. The choice to simulate at higher or lower building time step intervals depends on the thermal profile of the investigated space (e.g. high or low power density), thermal inertia of the building fabric (low or heavy thermal mass), whether seasonal scheduling is important or whether the site location can be characterized as being heating or cooling dominant.

Although not fully optimized at the time of the preparation of this paper, initial live tests show that the overall simulation time for estimating annual lighting, heating and cooling requirements and demand in single office and in classrooms is largely under a minute using building simulation time steps of 60 minutes, while it has been observed that open plan offices can take around one and a half minutes. This appears, however, to be only attributable to the much higher density of sensor points in the case of the latter room type. Overall, it seems clear that the proposed differential time scale solution offers acceptable accuracy while keeping simulation times under the set target for most cases.

CONCLUSION

The simulation experiment shows that the proposed solutions to enable differential time scales for dynamic boundary conditions within whole-building energy simulation, specifically occupant behavioral adaptations in response to dynamic solar and daylighting conditions (e.g. at 5 minutes) while keeping building time step duration at 1 hour, is indeed viable without substantially affecting simulation accuracy. Relative discrepancies were more strongly found for heating loads in single-occupancy offices, yet remained under 5% in all cases. Relative discrepancies in peak cooling demand in open-plan office environments approached 2%. Relative discrepancies for cooling loads and peak heating loads were all under 1% in all cases. This suggests some caution in heating dominant locations or for certain building typologies.

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