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Effects of furniture and contents on peak cooling load

Paul Raftery[a,*], Edwin Lee[b], Tom Webster[a], Tyler Hoyt[a], Fred Bauman[a]

[a] Center for the Built Environment, University of California Berkeley, Berkeley, CA, USA
[b] National Renewable Energy Laboratory, Golden, CO, USA

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ABSTRACT

We assess the impact that furniture and contents (i.e. internal mass) have on zone peak cooling loads using a perimeter zone model in EnergyPlus across 5400 parametric simulation runs. The zone parameters were HVAC system type (overhead, underfloor, and thermally activated building system (TABS)), orientation, window to wall ratio, and building envelope mass. The internal mass parameters were the amount, area, and the material type used. We also evaluated a new internal mass modeling method, which models direct solar radiation on the internal mass surface, an effect that is missing in current methods. We show how each of these parameters affect peak cooling load, highlighting previously unpublished effects. Overall, adding internal mass changed peak cooling load by a median value of −2.28% (−5.45% and −0.67% lower and upper quartiles respectively) across the studied parameter space. Though the median is quite low, this study highlights the *range* of effects that internal mass can have on peak cooling loads depending on the parameters used, and the discussion highlights the lack of guidance on selecting reasonable values for internal mass parameters. Based on this we recommend conducting an experimental study to answer outstanding questions regarding improved specification of internal mass parameters.

1. Introduction

Whole-building energy simulation is a widely used method to design and evaluate the energy performance of a building. The peak cooling load in each thermal zone in the model is often a key aspect of design, as it determines the size of the HVAC equipment needed to cool the zone sufficiently, which has affects energy performance throughout the year. It also influences the peak demand of the building.

A wide range of factors affect the peak cooling load in a thermal zone, such as:

- Solar radiation through fenestration;
- Transient conduction through zone surfaces;
- Internal gains (convective and radiant) from occupants, lights and equipment;
- Infiltration;
- The capacitive effects of the zone air volume;
- The HVAC system used to reject heat from the zone;
- The thermal inertia of the furniture and contents (internal mass).

This paper focuses on the effect that internal mass has on cooling loads, and how current simulation tools model these effects. There is considerable debate whether current practices yield sufficiently accurate instantaneous peak cooling load estimates. This also applies to heating loads, but is less critical because heating energy costs are not as time and peak sensitive as cooling energy costs.

Currently, the most detailed method to estimate these loads is to use a whole building energy simulation tool that assesses all aspects of heat exchange within a building simultaneously, and which captures temporal effects related to thermal inertia of the building elements. As with any simulation-based approach, simplifications and assumptions are necessary to reduce the complexity of the model. This ensures that the detail of the input parameters and the run-time of the simulation remain feasible for the particular application. This paper assesses how peak cooling loads are affected by internal mass and also discusses the effect of simplifications regarding current modeling methods in whole building energy simulation tools, and in particular, EnergyPlus.

1.1. Review of the surface heat balance

Modern whole-building energy simulation programs typically perform a detailed heat balance calculation at each surface in the model. The various heat transfer components within a thermal zone

* Corresponding author at: Center for the Built Environment, University of California, 390 Wurster Hall, Berkeley, CA 94720-1839, USA. Tel.: +1 510 643 6915.
E-mail addresses: p.raftery@berkeley.edu, research@paulraftery.com (P. Raftery).

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are comprehensively described in [1] and briefly reviewed here. The major components of heat transfer at each surface are:

- *Conduction*: Transient conductive heat transfer through a surface (either to the exterior environment or to other zones in the model) is often modeled using a transfer function or response factor approach [2], although some simulation programs, including EnergyPlus [3] also include a finite difference model as well. Any heat sources or sinks at depth within the surface (such as hot or cold water in hydronic tubing such as in a thermally active building system) also affect conductive heat transfer through the surface.
- *Short-wave radiation*: This is primarily due to solar radiation entering the zone through fenestration and typically has two components: direct and diffuse radiation. Whole-building energy simulation tools sometimes model direct solar radiation illuminating many zone surfaces, but often only the floor as a simplification. These methods avoid a detailed solar distribution calculation for each surface in the zone. Typically, the tools uniformly apply diffuse radiation (that either has entered through fenestration or has been scattered from direct solar radiation on zone surfaces) to surfaces using a surface area weighted average. The short-wave radiant component of lighting loads is typically added to the diffuse radiation.
- *Long-wave radiation*: Long-wave radiant exchange between surfaces in the zone is modeled using the temperatures of those surfaces, their emissivity, and calculated surface view factors. Long-wave radiative components of internals loads such as lighting, occupants, and equipment are typically applied uniformly across all surfaces using a surface area weighting.
- *Convection*: Convection from a surface is determined based on orientation, surface roughness, surface temperature and air temperature.

1.2. Review of the zone air heat balance

The combined result of the heat balance calculation at each surface lead to a heat balance for the zone air. Starting with the assumption that zone air is fully mixed, and adequately represented by a single temperature node, the rate of change of the zone air temperature is determined based on the following:

- The sum of the convective heat gains (or losses) from the surfaces in the zone;
- The convective components of the internal loads;
- The capacitance of the zone air and the amount of infiltration;
- The amount of heat removed (or added) by the air HVAC system.

The instantaneous cooling load of a zone is defined as the total cooling power required to maintain the zone air at the cooling setpoint temperature. For a all-air HVAC system, when the zone air is at the cooling set point, the cooling load the heat gained between the supply air and the return air. Two components comprise the cooling load for a thermally active building system (TABS) – the heat absorbed by the TABS element (e.g. the heat gained between the supply and return water in a hydronic slab system) and the heat gained between the supply air and the return air (the secondary ventilation air system).

1.3. Current methods for modeling internal mass

It is important to clarify a key point about internal mass modeling before continuing this discussion. In older simulation tools, or in studies that use simplified resistance-capacitance network modeling approaches, internal mass objects often represent structural building elements (such as floor slabs and other structural elements) as well as furniture and contents. This was necessary due to the broader assumptions and simplifications used in these tools regarding heat transfer, namely that they did not separately account for the thermal inertia of these structural elements. However, internal mass only represents furniture and contents in more modern tools (e.g. EnergyPlus and ESP-r) as these tools do capture the thermal inertia of structural elements. In this paper we assume internal mass refers to only the furniture and contents in the building, and that major elements of the building – the floors, walls and ceilings that separate discrete thermal zones – are explicitly modeled independently of the internal mass object.

Traditionally, internal mass within zone heat balance calculations has been implemented using a simplified approach where the internal mass occupies the zone without regard to the shape or location of the furniture (i.e. the geometry). Following on from mathematical studies focused on this topic [4], numerous experimental [5] and simulation based studies [6–11] have been performed on how thermal mass can be designed to minimize energy use in a building. Internal mass within zones has been modeled using a lumped thermal network approach used as part of an inverse modeling process that uses a parameter estimation technique to determine internal mass thermal properties from experimental data [12]. Some studies use an inverse approach in which ideal thermal properties of building materials are evaluated in order to minimize the energy usage of a building [13], which is in contrast to a typical building simulation process that involves specifying building and mass material properties. Although there are a range of modeling approaches used in the simulation studies, one common factor is that all of them use a simplified internal mass model that does not account for geometry. These studies also use a single node (or at most two nodes) to represent all the thermal mass within a zone (or often even the whole building), including the furniture (where this is explicitly mentioned in the study), internal walls, floors, and ceilings.

Within EnergyPlus [14], an internal mass object consists of a defined construction (a one-dimensional set of discrete layers, each with separate thermal properties) and an exposed surface area that interacts with the zone heat balance on one side of the surface and has an adiabatic boundary condition on the other side. Because this is not a geometric description, direct solar radiation illuminates the zone surfaces in the model but not the thermal mass surface. Aside from this difference, EnergyPlus accounts for all elements of the surface heat balance method described in Section 1.1 for each internal mass surface exactly as it would for any other surface in the model.

1.4. Problem statement

We start from the assumption that the model in question explicitly represents each of the surfaces enclosing a thermal zone independently. Internal mass then solely refers to the furniture and contents in a zone. As described in Section 1.3, all of the approaches to date use a geometrically simplified internal mass, even when described independently from other surfaces within the zone. This is because it is generally intractable to consider furniture in a detailed fashion in a whole-building energy simulation environment. Under the current assumptions of the most detailed modeling engines, internal mass interacts with: (a) the zone air through convection, (b) diffuse radiation in the zone assuming a uniform surface area weighted exchange, (c) long-wave radiation exchange assuming a uniform surface area weighted exchange. We assume that each of these approaches is valid, appropriately detailed representations of the underlying processes given current limits to computing capabilities. The missing piece in this representation is an approach that couples the internal mass to direct solar radiation, and considers the partial shading of the floor underneath.