Integrating active thermal mass strategies with HVAC systems in office buildings: development of a concept design tool

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ABSTRACT

Thermal mass can be used in buildings to reduce the need for and dependence on mechanical heating and cooling systems whilst maintaining environmental comfort. Active thermal mass strategies further enhance the performance of thermal mass through integration with the Heating, Ventilation and Air Conditioning (HVAC) systems. For the design of new buildings to include active thermal mass strategies, experience from operational projects and design guidelines are normally used by engineers. However, dynamic thermal modelling is required in most cases to accurately determine the performance of its integration with the environmental systems of the building. Design decisions made in the preliminary stages of the design of a building often determine its final thermal characteristics. At this stage, reasons for not integrating active thermal mass strategies include the lack of knowledge about the performance of previous buildings and the time and resources required to carry out detailed modelling.

This paper outlines a simplified design tool that can be used at the concept design stages of a typical office building to determine the benefits of integrating an active thermal mass strategy. This was developed by carrying out simulations using a dynamic thermal model which was calibrated by measurements in operational buildings with active thermal mass in the UK. Four active thermal mass strategies are considered (a) hollow core slabs (b) earth-to-air heat exchanger (c) floor void with mass and (d) thermal labyrinth in addition to a standard office with no active thermal mass. Key design parameters were identified for each system and parametric analysis was carried out to determine the resulting environmental conditions and energy consumption in the office.

The tool has an easy-to-use interface which allows direct comparison of the different active thermal mass strategies together with the effects of changing key design parameters. Results are presented in terms of thermal comfort and energy consumption.

1. INTRODUCTION

A buildings fabric and form are developed at a very early stage of the building design process with the building services engineers frequently having to design their services and strategies around relatively finalised buildings, not having an input into the orientation, form or layout of the building, making the building services an 'add-on' to the building instead of an integrated part of the building.

The decisions made on the building fabric, form and orientation will determine the

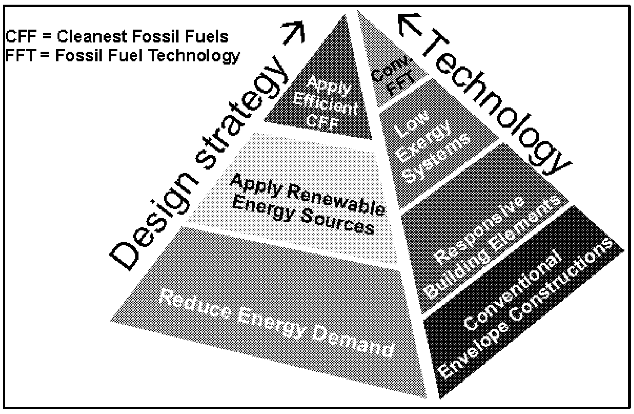

Figure 1: Illustration of IEA Annex 44 Design Strategy

buildings performance throughout its lifetime (Sorell, 2003) so it is important that they are considered as part of an integrated design process.

As part of the IEA-ECBCS Annex 44 a strategy has been developed for the integration of Responsive Building Elements (see figure 1), into which active thermal mass strategies fit. This shows that for the best integration, Responsive Building Elements together with the envelope construction need to be considered at the early stages of the design process.

Building simulation, simplified guidelines and expert advice based on experience can be used to support building design (deWit & Augenbroe, 2002). However, simulation requires detailed information about the building that may not have been decided at the early stages (Ghiaus *et al.,* 2006) making it more suitable for detailed energy analysis in the later stages of design (Shaviv, 1998; Al-Homoud, 2001; Olsen *et al.,* 2003; Clarke *et al.,* 2004).

Simplified guidelines are available for some active thermal mass strategies, but they relate to the performance of the active thermal mass and do not consider the integration and how they will perform when integrated with a building under different load conditions.

Expert advice based on design experience is also project specific and cannot be used for buildings under different load conditions with confidence.

There is therefore a requirement for design tools that can be used at the concept design stages of a building to analyse the effects of integrating active thermal mass strategies into buildings for a range of design parameters.

This paper describes the rationale and methodology for the development of a concept design tool for evaluating the effect of integrating active thermal mass strategies.

2. METHOD OF TOOL DEVELOPMENT

To allow the effects of integrating an active thermal mass strategy into an office building, together with the effects of space design and use, a number of parameters have been explored.

These parameters can be split into two categories; fixed parameters and user selected parameters.

The fixed parameters are pre-selected for the design tool and have to be a fair representation of the projects that the tool will be used for.

The user selected parameters are chosen by the user to represent the way the building will be used, and to look at the effect of key design decisions on the performance of the building.

2.1 Fixed Parameters

2.1.1 Office Type

The simulation results were based on a single office cell 10m wide, 6m deep and 3m high (Tindale *et al,* 1995; Kolokotroni *et al,* 1997; CIBSE, 2002a; Kolokotroni *et al*, 2004). The cell has one external wall and is located on a middle floor with the rooms above and below conditioned similarly to the test room (see figure 2).

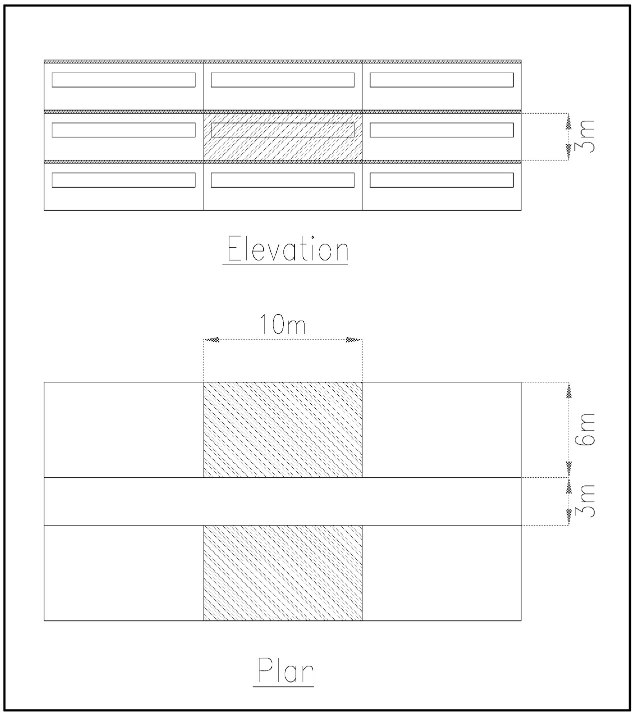

Figure 2: Plan and elevation of typical office

2.1.2 Weather Data

The model has been simulated using CIBSE Design Summer Year (DSY) 2005 weather data for London (CIBSE, 2002b).

2.2 User Selected Parameters

2.2.1 Active Thermal Mass Strategy

Active Thermal Mass Strategies can be used to enhance the performance of thermal mass by passing air or fluid across the surfaces with high thermal mass (Russell *et al,* 2001). Four Active Thermal Mass Strategies can be selected:

a) Active Hollow Core Slabs: Hollow core pre-cast concrete slabs are used as a path for supply air thus increasing the coupling between the thermal mass and the supply air (Ren & Wright, 1997) attenuating variations in ambient air temperatures (Barton *et al,* 2002).

b) Floor Void with Thermal Mass: A void created between a raised floor and a structural concrete slab as a supply air plenum, again increasing the coupling with the thermal mass and supply air (Nagano *et al,* 2006).

c) Earth to Air Heat Exchanger: An earth-to-air heat exchanger draws ventilation air through ducts buried underground (Zimmerman & Remund, 2001; Santamouris, 2006).

d) Thermal Labyrinth: A thermal labyrinth decouples the thermal mass from the occupied space by creating a concrete undercroft, increasing the surface area of thermal mass, beneath the building. The benefits of decoupling the mass are that it can be cooled lower than if it was in the occupied space and the stored 'coolth' can be used to condition the occupied period for up to 3 or 4 days in hot periods (Cook & Rees, 2006).

2.2.2 Service Strategy

When a space has high internal heat gains an active thermal mass strategy will not have enough storage capacity to overcome these loads and provide a comfortable environment. In these cases cooling may be required. To analyse the effect an active thermal mass strategy has when coupled with a cooling system two different service strategies can be selected.

a) Mechanical Ventilation – the supply air is heated to meet the heating load of the test room in the winter period; in the summer period ambient air is supplied directly to the test room.

b) Comfort Cooling - the supply air is heated to meet the heating load of the test room in the winter period; additionally the supply air is cooled to meet the cooling load of the test room in the summer.

2.2.3 Air Flow Rate

The internal heat gains, and therefore the occupancy, together with the solar gains to the test room are changeable within the tool. The amount of air required to achieve the minimum fresh air rate or the amount of air required to meet the cooling demand of the space therefore varies. Air change rates of 1, 2, 6, 8 and 10 $achr^{-1}$ have been included to allow the user to select an air flow rate suitable for the internal and solar gains that have been selected.

Table 1: Internal Heat Gains

	Density of Occupation ($per{\cdot}m^{-2}$)	Sensible Heat Gain ($W{\cdot}m^{-2}$)	Latent Heat Gain ($W{\cdot}m^{-2}$)
High	4	57	15
Medium	8	42	7.5
Low	20	26	3

2.2.4 Internal Heat Gains

The internal heat gains were defined using data from CIBSE Guide A (CIBSE, 2006a). Three levels of internal heat gain can be selected (see table 1).

2.2.5 Night Cooling

Night cooling is a low energy strategy for maximising the benefit of internal thermal mass (Kolokotroni, 1998). Ventilation is used to cool the internal surfaces of a building at night. During the following day a portion of the buildings heat gains are then absorbed by the cooler building fabric. Night cooling can be selected and is controlled based on the strategy developed within BSRIA Technical Appraisal 14/96 (Fletcher & Martin, 1996).

2.2.6 Solar Gains

The method outlined in CIBSE TM37 (CIBSE, 2006b) has been used to classify the solar gains to the test room in terms of solar gain per unit floor area (m^2) over the period 0630 to 1630 Solar Time (GMT). By exploring different glazing areas and shading coefficients, three levels of solar gains have been determined: Low 10 $W{\cdot}m^{-2}$, Medium 20 $W{\cdot}m^{-2}$ and High 30 $W{\cdot}m^{-2}$. A glazing area of 40% has been used for all of the solar gains, except when the facade faces north where a glazing area of 60% was required to achieve medium solar gains and 90% to achieve high solar gains. The shading coefficients of the glazing have been adjusted to achieve a low, medium and high configuration for north, east, south and west orientations.

2.2.7 Building Thermal Weight

Interior mass within a building's internal structure (floors, partitions, etc) creates a heat sink into which internally generated heat can be absorbed and stored during the occupied period.

Rennie and Parand (1998) defined the thermal mass by the room admittance per m^2 floor area and categorised the different levels as: Very Light 6 to 8$W{\cdot}m^{-2}{\cdot}K^{-1}$, Light 8 to 10 $W{\cdot}m^{-2}{\cdot}K^{-1}$, Heavy 14 to 18 $W{\cdot}m^{-2}{\cdot}K^{-1}$ and Very Heavy 18 to 24 $W{\cdot}m^{-2}{\cdot}K^{-1}$.

To give a fair representation of this spectrum four typical groups of construction have been created allowing the user to select the level of thermal mass (see table 2).

The amount of insulation in the external walls has been set to achieve a CIBSE U-value of 0.35 $W.m^{-2}.K^{-1}$, which is the limiting area weighted average U-value required to meet the requirements of Building Regulations Approved Documents Part L2A for England and Wales (OPDM, 2006).

Table 2: Typical groups of construction

Element	Very Light	Light	Heavy	Very Heavy
	$W{\cdot}m^{-2}{\cdot}K^{-1}$			
External Wall	0.85	2.73	5.53	5.53
Internal Wall	0.75	2.65	4.13	4.13
Floor	2.57	2.57	2.72	6.26
Ceiling	2.86	2.86	6.09	6.13
Admittance per m^2 floor area	6.39	8.78	14.39	17.96

2.2.8 Orientation

Although the selected solar gains controls the amount of solar heat gain to the space, the orientation still effects the time of day that the gains are experienced by the room. Orientations of North, East, South or West can be compared.

2.2.9 Additional Options

Additional to the main user selected parameters described above, the user can also select options that will affect the amount of energy consumed by the fan and the amount of energy consumed for heating and cooling.

The system pressure and the fan efficiency alter the energy consumption of the fan. If it is known at the early stages of design that long lengths of ductwork will be needed or energy efficient fans are to be used this will greatly effect the energy consumption. The system pressure and the fan efficiency can therefore be selected by the user.

The boiler efficiency and chiller coefficient of performance together with the distribution losses directly effect the energy consumption and can also be selected by the user.

Another key option the user can select is the amount of heat recovery for both heating and cooling.

3. SIMULATIONS & USER INTERFACE

Concept design tools can be divided into two main categories (Kolokotroni *et al,* 2004):

- Results are extracted from built-in databases derived from advanced modelling for a specified number of cases (in the form of parametric analysis) and weather data (usually country restricted).
- Results are calculated from built-in (usually energy and thermal) simplified or fast-to-run algorithms.

It was chosen to develop the tool using the 'database' approach. This was for two reasons (1) the results would be based on detailed and advanced modelling allowing the use of calibrated models, and therefore more accurate (2) misinterpretation of the results would be more difficult due to the options within the design tool being restricted.

Dynamic thermal models calibrated by measurements from operational buildings with active thermal mass strategies in the UK were used to carry out simulations for all of the combinations of the parameters above (900 simulations).

A database was created with the simulation results and a user interface was created within Microsoft Excel. A description of the available outputs for the user are presented below.

The database allows the user to select a base option and four other options for comparison.

The tool is one of the outputs of the IEA-ECBCS Annex 44 and will be available from the website www.ecbcs.org/annexes/annex44.

4. DESCRIPTION OF OUTPUT RESULTS

The output results are presented on two different levels; summary results and detailed results.

4.1 Summary Results

The summary results are a single page printout intended to give a quick snapshot of the performance of the different options. The results are presented in a graphical format of the actual values and in a tabular format that express the results as a percentage of the base option
allowing quick comparison between the different options.

4.1.1 Heating Energy Demand

The energy (normalised per m^2 floor area) required to maintain the test room air temperature above the heating setpoint (21^{o}C) during the occupied hours for a full year.

4.1.2 Cooling Energy Demand

The energy (normalised per m^2 floor area) required to maintain the test room air temperature below the cooling set point (24^{o}C) during the occupied hours for a full year. Only applies if comfort cooling is selected.

4.1.3 Overheating Hours

The number of hours the dry resultant temperature in the test room exceeds 24, 25, 26, 27 and 28^{o}C.

4.1.4 Fan Energy Demand

The energy required to run the fan to supply the air to the test room. This allows the benefits of adding night cooling to be compared against the additional energy required by the fan.

4.2 Detailed Results

To allow the user to look at the results in more detail there is a separate page for heating energy, cooling energy and overheating hours that break the results down into monthly energy consumption and looks at the energy and room temperatures during a peak week and a peak day. The results are again presented in a graphical format for the actual results and in a tabular format that express the results as a percentage of the base option.

5. CONCLUSIONS

This paper described the methodology used for the development of a concept design tool to help designers analyse the effects, in terms of energy and comfort, of integrating active thermal mass strategies into office buildings for a range of design parameters.

The results from simulations using a calibrated dynamic thermal model have been used to create a database within Microsoft Excel. The user can select one base option together and four other options for comparison.

The results are then presented in two levels; summary results and detailed results.

The summary results present the heat energy demand, cooling energy demand, fan energy demand normalised per m^2 floor area together with overheating hours in a graphical format of the actual values and in a tabular format that express the results as a percentage of the base option allowing quick comparison between the different options.

To allow the user to look at the results in more detail there is a separate page for heating energy, cooling energy and overheating hours that break the results down into monthly energy consumption and looks at the energy and room temperatures during a peak week and a peak day. The results are again presented in a graphical format for the actual results and in a tabular format that express the results as a percentage of the base option.

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