The role of thermal mass on the cooling load of buildings. An overview of computational methods

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Abstract

Thermal mass can reduce peak cooling loads and indoor air temperature swings in buildings. The factors affecting the performance of thermal mass are reviewed and classified. Experimental studies which demonstrate the effectiveness of thermal mass as an energy conservation alternative and in providing more comfortable indoor conditions, are also reviewed. A number of simplified design tools for calculating the cooling load and indoor air temperatures of a building, which also account for thermal mass effects, have been identified and are classified. The models are categorized in terms of their inputs, outputs and restrictions on their level of accuracy in treating thermal mass effects, type of loads or other design limitations.

Keywords: Thermal mass; Cooling load; Computational methods

1. Introduction

Indoor air temperature is primarily influenced by external climatological parameters (solar radiation, outdoor temperature) and highly variable internal loads (human activity, lights, equipment). During the summer, this results in temperature swings, with peaks occurring around noon and early afternoon hours. During these periods of the day, high outdoor temperatures eliminate the use of simple alternative passive cooling techniques like natural ventilation. As a result, in order to maintain thermal comfort during these hours, it is necessary to remove all excess heat from the space immediately upon entry, by an energy consuming mechanical system. This will require an oversized system capable of handling the short period peaks of the cooling load.

To reduce indoor air temperature and cooling load peaks, and to transfer the load to a later time in the day, it is possible to store heat in the material of the outer envelope and the interior mass of the building. The storage material is the construction mass of the building itself, which is referred to as thermal mass. It is typically contained in walls, partitions, ceilings and floors of the building, constructed of material with high heat capacity, such as poured concrete, bricks and tiles.

The thermal mass of the building could have a positive effect on the indoor conditions during the summer and winter periods. The energy available from the high solar gains during the day is stored and then is slowly released into the indoor environment at a later time. In winter, the stored heat is transferred back into the room during the late afternoon and late evening hours, when it is most needed, satisfying part of the heating load and avoiding overheating and discomfort conditions during the high solar radiation periods of the day.

In summer, heat is stored in the thermal mass, thus reducing the cooling load peaks. A reduced portion of the load will need to be removed from the interior space, while the remaining portion of the external and internal heat gains is contained within the thermal storage materials. The stored heat is progressively released to the interior of the building. As a result indoor air temperature variations remain within the comfort range, for most hours during the day. This then reduces the energy consumption for cooling, which can reach 20% in commercial buildings [1].

There is also a time shift of the peak load and a time lag of the heat release from the material to the indoor air. This time lag is actually desirable, since at the time when the heat is returned to the interior, the indoor temperature is relatively lower. In the event that the building is also unoccupied during the evening hours, like office buildings, it is possible to relax the restrictions on indoor thermal comfort. In any event, outdoor conditions are more favourable for passive cooling techniques, like natural, hybrid or indirect ventilation, which can be used to remove portions of the load [2].
The effectiveness of thermal storage is acceptable where the diurnal variation of ambient temperatures exceeds 10 K [3]. Under such circumstances, ample night ventilation and closing the building during the day, due to the thermal mass effect, it is possible to achieve a temperature difference, between the mean indoor and outdoor temperatures, greater than 10 K in the negative direction and an indoor temperature swing of 2.5 K.

Thermal mass has also a positive effect on occupant comfort. High mass buildings prohibit high interior air and wall temperature variations and sustain a more steady overall thermal environment. This increases comfort, particularly during mild seasons (spring and fall), during large air temperature changes (high solar gain), and in areas with large day–night temperature swings (high solar gain). Traditional architecture, especially in southern European countries, has successfully demonstrated these positive effects.

2. Parameters affecting the performance of thermal mass

The rate of heat transfer through and the effectiveness of thermal mass are determined by a number of parameters and conditions. To achieve the best possible results, one needs to follow some general guidelines and take appropriate actions that fall within the overall procedure for energy efficient building. It is important though to also understand the relation of these parameters on the performance of thermal mass in order to achieve the best possible results. Optimization of thermal mass levels depends on building material properties, building orientation for its location and distribution, thermal insulation, ventilation, climatic conditions and use of auxiliary cooling systems, and occupancy patterns. The most important features, for each of these parameters, are presented in the following discussion.

2.1. Material thermal properties and performance

The temperature distribution within the building materials varies with time, boundary conditions and material thermal properties. The phenomena which take place during day and night periods, differ significantly, depending on whether the mass material is being charged (temperature increase) or discharged (temperature decrease), respectively.

The thermophysical properties of heat storing material can influence the performance of the system. For the material to effectively store heat, it must exhibit a proper density, high thermal capacity, and a high thermal conductivity value, so that heat may penetrate through all the material during the specific time of heat charging and discharging.

The depth that the diurnal heat wave reaches within the storage material depends on thermal diffusivity (the controlling transport property for transient heat transfer). Materials with higher thermal diffusivity values can be more effective for cyclic heat storage at greater depth than materials with lower values. Beyond a certain material thickness, the heat flow into the indoor air does not take place during the night hours, but it is delayed till the following daytime hours. This is undesirable during the cooling season, since the release of stored heat to indoor spaces during the early hours of the day will result in unpleasant indoor comfort conditions and increase early day cooling loads.

2.2. Thermal mass location and distribution

Location of thermal mass is important. One may distinguish two cases, based on whether the heat storage material receives energy by solar radiation (direct) or by IR radiation and room air convection (indirect). Direct heat gains are experienced by the outer building envelope, which is exposed to solar radiation and by the interior surfaces which may absorb incident solar radiation as it enters through the building’s openings. Indirect heat gains are experienced by opaque elements inside the building from the energy which is transferred indoors from direct gain surfaces. Direct locations are much more effective than indirect, for placing heat storage mass.

Thermal mass must be properly distributed around the building depending on the orientation of a given surface and the desirable time lag [5]. North and east surface orientations have little need for time lag. For a south and west side, an 8 h time lag is sufficient to delay heat transfer from midday until the evening hours. The roof, which is exposed to solar radiation during most hours of the day, would have required a very heavy construction with a long time lag. However, because it is very expensive to construct massive roofs, the use of additional insulation is usually recommended instead.

2.3. Thermal mass and insulation

In general, both thermal mass and insulation are important in the overall thermal performance of a building [6]. In climates where cooling is of primary concern, thermal mass can reduce energy consumption provided that the building is unused in the evening hours and the stored heat can be dissipated during this idle period. However, common insulation materials will deteriorate the performance of a thermal storage wall [7]. Overall, because thermal mass stores and releases heat, it interacts with the building operation more than the simple addition of insulation [8]. This makes analyzing thermal mass performance and the overall building thermal performance a more difficult problem to treat.

2.4. The role of ventilation

The role of thermal mass is also extended into the night period. During the summer, since outdoor night temperatures are usually lower than indoor temperatures, it is possible to cool the building by natural night ventilation. Ventilated air enhances convective heat losses from mass elements and dissipates the released heat to the lower temperature outdoor
heat sink. Ceiling fans can also be used to increase indoor air movement and raise the convective heat transfer coefficient, which facilitates the process of rejecting heat from massive walls at night [9]. The recommended night ventilation hourly rate is 90 m$^3$/h m$^2$ of floor area. The objective is to maximize the building thermal transmittance during the nighttime and minimize it during daytime.

When the climatic conditions do not permit the use of outdoor air, because of high humidity levels, one can still precool the building during off-peak hours, using an air-conditioning system. This, in fact, results in considerable savings to the user and to the electric utility [10–13]. The electricity rates at night are usually much lower, since the demand drops considerably. On the other hand, the utility company also benefits, since eventually there will be a smaller demand during the day hours, which in turn reduces the need for additional generating capacity and maintains a more uniform load on the power generating facility. The saving is achieved by subcooling the mass immediately before the peak utility rate period, thereby shifting a portion of the cooling load off-peak [12].

At the beginning of the following day, the cooled mass is utilized as a heat sink. Part of the cooling load will be passively covered by the building mass which is at a lower temperature, provided that the building is well insulated and is not ventilated during the daytime. This means that for air-conditioned buildings it is possible to reduce the energy consumption of the system, since it will reduce its operation time. For naturally ventilated buildings it is possible to achieve longer periods within comfort conditions.

2.5. Occupancy patterns

A designer, should keep in mind that building occupants constitute the final determining factor on the extent of utilizable energy of any building system, including thermal mass. Clearly, by changing the use of internal spaces and surfaces one can drastically reduce the effectiveness of thermal storage. Consequently it is necessary to carefully consider the final use of the space when making calculations of the cooling load and incorporating the possible savings from thermal mass effects.

3. Effectiveness of thermal mass

The effect of building thermal storage on the peak cooling load has been evaluated during an experiment with a large office building in Jacksonville, Florida [14]. The objective was to precool the building at night and during the weekend, to reduce daytime cooling loads. Diurnal heat capacity calculations were used in analyzing the experimental results. The results showed an 18% reduction in cooling energy supplied during daytime.

A theoretical analysis of data collected during an extensive monitoring campaign of office buildings, using variable levels of thermal mass in similar buildings, has provided useful information [15]. Accordingly, an increase of thermal mass from 21 to 201 kg/m$^2$ of floor area, in close and in ventilated buildings, can reduce the peak indoor temperature by approximately 1 and 2°C, respectively. Important reductions in peak heating and cooling loads can be achieved for high thermal mass designs. Energy savings vary between 18 to 20%, compared to a base case.

A high mass test house was monitored in an environmental chamber under a nighttime cooling operation [16]. The cooling load was measured for simple cyclic outdoor climatic conditions. The simulated outdoor conditions were for a desert type climate (low temperatures and high humidity at night, and hot and dry conditions during the day). Nighttime cooling was proved to be much more efficient than 24 h cooling, resulting in over 50% decrease of the total daily electric power consumption. For cooling load calculations, under these climatic conditions, it is however important to account for a large amount of latent cooling load, resulting from the release of moisture from the structural concrete during the daytime warm-up period.

For indoor temperatures set at 24°C, heavyweight buildings have been reported to consume less cooling energy than comparable lightweight buildings having the equivalent thermal resistance in their walls [17]. The thermal mass was also found more effective when it was positioned inside the wall insulation. Nighttime ventilation can reduce cooling loads by 27 to 36%, depending on the wall construction of the building. Larger savings occur in heavyweight compared to lightweight buildings.

Robertson [4] has presented specific recommendations on how to best use thermal mass materials in residential and small commercial buildings, for southwestern United States locations. Dense and usually more conductive building materials are better. A 5–10 cm wall thickness is usable for heat absorption, storage and release on a daily basis. Thicker walls, up to 25 cm, may provide longer periods of thermal storage. Thermostat setup during summer, is less effective in massive structures, because they take longer to cool down. Numerical simulations have also shown that the percent annual reductions in sensible heating and cooling loads, because of the thermal mass levels of the walls (floors and foundations were assumed to be massless), can be as high as 40% in mild climates.

For the designer, experimental results provide useful information, but for actual building design one needs appropriate tools to be able to deal with specific applications. There are several design and computational tools available, which take into account the impact of thermal mass on the building's thermal performance. In a recently completed study, 128 programs have been identified, that have some capabilities to calculate the cooling load of a building [18]. Among them, 54 programs can also calculate the variation of the indoor air temperature, 45 programs can also take into account the impact of mass and shading, while only 23 programs can also simulate natural ventilation strategies.
4. Simplified design tools

In total, 16 simplified models for estimating the cooling load of a building, taking into account the building’s thermal mass, have been selected and are briefly described in the following discussion, in alphabetical order. Simplified design tools are necessary for building designers during the first stages of a design process in order to evaluate new techniques and systems and their performance under specific conditions. These tools are easy to use, do not require detailed inputs and provide relatively accurate information. They may require the use of a computer or in some cases the calculations can also be performed by hand.

The reviewed models are tabulated in Table I, which includes some relevant information for each one. For each method, one can identify the inputs and outputs, the parameter used to account for the thermal mass effect, the restrictions and whether the method has been used to develop a software package. This review has also revealed a number of parameters which can be used to account for the thermal mass effect on the cooling load and overall behaviour of buildings. These parameters and their physical meaning are summarized in Table 2.

4.1. Description of models

ASHRAE [19] has adapted a simplified design method. The calculations can be performed by hand using a few fundamental equations but numerous tabulated input data. The thermal mass effect on the cooling load is taken into account by various factors, called cooling load temperature differences (CLTD) and cooling load factors (CLF). These factors were generated for each component of the space cooling load using the methodology and basic equations of the transfer function method (TFM). Following the TFM procedure, extensive computer simulations were first carried out, and then based on these results, the representative multipliers (CLTD and CLF values) were extracted by dividing component results by their U value. The space cooling load components are calculated directly, using tabulated CLTD and CLF, which include the effect of time lag due to thermal storage. The method can account for the significance of the thermal mass on the cooling load for light, medium and heavy building constructions, but it cannot directly handle the calculation of optimum thermal mass level and distribution. An additional limitation of the method is that the tabulated factors have been calculated for a constant indoor air temperature, an assumption which is not valid for buildings where temperature swings are expected. A modification of the CLF factor to account for external window shading, has been proposed by Todorovic [20]. This so-called ‘negative cooling load’ method provides more accurate results with differences that can be as much as 50% [21].

The Athienitis model [22,23] is particularly suitable for massive buildings. It is a predictive control algorithm which utilizes computer prediction of the building’s response to expected weather inputs to modify its operation strategy so as to reduce energy consumption and temperature swings resulting from large solar and other radiant gains, and highly variable loads. The model is developed for a heating season. The building response to expected weather inputs and internal gains is predicted using a frequency domain thermal network model. Using an iterative technique, a profile of the thermostat set point is determined so that optimum comfort and minimum energy consumption are achieved. The building model employs distributed elements, such as thermal storage mass in walls, accounts for thermal coupling between rooms, room interior radiant exchanges, and a time varying conductance.

The Bida and Kreider model [24] is a simplified design method which can be used for calculating the monthly cooling loads of dwellings and small multistorey buildings, with small internal gains. The main source of heat which is transferred into the building is from incident solar radiation. The interior of the building is considered as one zone. The component of the cooling load from the latent heat is not taken into account. However, the model accounts for loads from ambient and internal gains, and solar gains through transparent and opaque elements. The mass effect coefficient (MEC) is used to account for thermal mass effects on the cooling load and is defined as the ratio of the calculated monthly cooling load to the monthly cooling load if no thermal mass were present. The model can estimate the annual cooling loads with an acceptable accuracy. For large cooling loads, greater than 10 GJ/year, the maximum error is less than 15%. The calculations of the cooling load can be performed for light and heavy buildings, thus enabling the user to easily compare the effectiveness of the thermal mass in reducing the cooling load of a building.

The Building Research Establishment [25] has developed a method for calculating peak summer temperatures. The method introduces the concept of the admittance factor. This represents the extent to which heat enters the surface of materials in a 24 h cycle of temperature variation. This follows from the fact that dense materials take up more heat and have higher admittance values than lightweight ones. The method has been developed in an easy to follow format of a series of worksheets that the user has to fill out and includes the effect of material thermal capacity and resistance. It is suitable for office buildings, with one external wall and all other faces about other offices, but it can be extended for treating rooms not surrounded by others, with a reduced accuracy.

Catani [26] has developed a computer program accounting for thermal mass effects. The method is known as the M factor, which is a correction to steady-state R values that can result in less insulation being required in opaque wall sections of massive buildings than for lightweight buildings. Charts of M factors show the correction as a function of local degree days and the weight per unit of wall area. The M factor is used to indicate the thermal performance of building envelopes and as a correction to the steady state U values, which are divided by this factor. Accordingly, the M factor is a...
Table 1
Simplified design tools for calculating the cooling load in buildings

<table>
<thead>
<tr>
<th>Model</th>
<th>Inputs</th>
<th>Outputs</th>
<th>Parameter to describe mass thermal effects</th>
<th>Restrictions</th>
<th>Software</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. ASHRAE [19]</td>
<td>BG,BC,IL,EL,AT/M,VE/S and L</td>
<td>hourly and peak cooling loads</td>
<td>CLTD values for wall construction</td>
<td>simplified treatment</td>
<td>no</td>
</tr>
<tr>
<td>Todorovic [21]</td>
<td>IN/S and L</td>
<td></td>
<td>modified CLF for windows</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Athienitis [22]</td>
<td>BG,BC,AT/M,AT/H,SR/M or SR/H,IL</td>
<td>hourly or monthly for elements in a thermal network</td>
<td>detailed inputs, complex analysis</td>
<td>yes</td>
<td></td>
</tr>
<tr>
<td>4. BRE [25]</td>
<td>BG,BC,EL,IL</td>
<td>peak summer temperatures</td>
<td>admittance factor</td>
<td>All external input functions are taken equal, no wind effects</td>
<td>no</td>
</tr>
<tr>
<td>7. Givoni and Hoffman [30]</td>
<td>BG,BC,VE,SR/M,AT/M</td>
<td>internal air temperature</td>
<td>total thermal time constant</td>
<td>All external input functions are taken equal, no wind effects</td>
<td>yes</td>
</tr>
<tr>
<td>8. Kusuda [31]</td>
<td>BG,BC,IL,VE,TA/H,SR/H</td>
<td>transient sensible cooling load</td>
<td>conduction transfer functions</td>
<td>Detailed inputs, complex analysis for multi-zone, element cases</td>
<td>no</td>
</tr>
<tr>
<td>9. LANL [36]</td>
<td>BG,BC,SR/M,DD</td>
<td>monthly cooling load, daily average indoor temperature</td>
<td>solar saving fraction</td>
<td>Restricted to certain type of buildings, no VE, IL, wind effects</td>
<td>yes</td>
</tr>
<tr>
<td>10. van der Maas and Roulet [37]</td>
<td>BG,BC,IL,AT,VE/S</td>
<td>indoor air temperature, cooling rate</td>
<td>thermal effusivity</td>
<td>Monozone, stack effect driven flows, short periods, homogeneous walls, no radiation, no convective effects, constant heat flow rates, no wind effects</td>
<td>yes</td>
</tr>
<tr>
<td>11. Mathews and Richard [38]</td>
<td>BG,BC,IL,EL,VE,SR/M, AT/M</td>
<td>hourly indoor air temperature and sensible loads</td>
<td>effective heat storage and sensible loads</td>
<td>Single zone, no temperature stratification, interior surfaces at same temperature, no wind effects</td>
<td>yes</td>
</tr>
<tr>
<td>12. Passport Plus [41]</td>
<td>DG,BC,IL,IN/S/L,VE/S</td>
<td>hourly indoor air and surface temperatures, cooling/heating load, air flows, comfort</td>
<td>transfer functions</td>
<td>One dimensional heat conduction</td>
<td>yes</td>
</tr>
<tr>
<td>AT/H,SR/H,WV/H,WD/H</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Meteorological Library files)</td>
<td>BG,BC,SR,DD</td>
<td>monthly cooling load, daily average cooling load</td>
<td>heat capacity</td>
<td>no VE, IL, wind effects</td>
<td>yes</td>
</tr>
<tr>
<td>13. PMDO [36]</td>
<td>BG,BC,SR,DD</td>
<td>hourly indoor air and surface temperatures, cooling/heating load, air flows, comfort</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14. Seem [33]</td>
<td>Previous temperature and heat flux, transfer functions, loads for AT,IL,EL</td>
<td>comprehensive transfer functions</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(continued)
### Table 1
(continued)

<table>
<thead>
<tr>
<th>Model</th>
<th>Inputs</th>
<th>Outputs</th>
<th>Parameter to describe mass thermal effects</th>
<th>Restrictions</th>
<th>Software</th>
</tr>
</thead>
<tbody>
<tr>
<td>15. Shaviv [43,44]</td>
<td>BG, BC, SR/H, AT/H</td>
<td>maximum indoor temperature</td>
<td>heat capacity, thermal resistance</td>
<td>isothermal internal mass</td>
<td>no</td>
</tr>
<tr>
<td>16. SPIEL [46]</td>
<td>BG, BC, SS, AT/M, IN</td>
<td>mean monthly hourly indoor air temperature, cooling load</td>
<td>capacitance</td>
<td>convergence of calculated values, no direct account of SR levels, no IN, no wind effects</td>
<td>steady state conditions, no IL/EL/VE</td>
</tr>
<tr>
<td>17. Steady State [17]</td>
<td>BG, BC, AT/M, IN</td>
<td>average daily space cooling</td>
<td>envelope heat transfer coefficient</td>
<td></td>
<td>no</td>
</tr>
</tbody>
</table>

Nomenclature: ADT = monthly ambient daytime temperature; AT/M, AT/H = ambient temperature monthly data, ambient temperature hourly data; BC = detailed information on the building construction (U values, material thermal properties); BG = detailed information on the building geometry, orientation; CDD = monthly cooling degree days; CL = monthly clearness index; DD = monthly degree days; EL = external loads (solar radiation, temperature); IL = internal loads (human activity, equipment, lights); IN/S, IN/L = infiltration loads from sensible heat, infiltration loads from latent heat; SR/M, SR/H = solar radiation monthly data, solar radiation hourly data; SS = mean daily sunshine hours; VE/S, VE/L = ventilation loads from sensible heat, ventilation loads from latent heat; WV/M, WV/H = wind velocity monthly data, wind velocity hourly data; WD/M, WD/H = wind direction monthly data, wind direction hourly data.

### Table 2
Parameters for describing thermal mass effects

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Physical meaning</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Admittance factor</td>
<td>represents the extent to which heat enters the surface of materials in a 24 h cycle of temperature variation</td>
<td>[25]</td>
</tr>
<tr>
<td>Capacitance</td>
<td>accounts for the ability of the external and internal materials to store heat</td>
<td>[49]</td>
</tr>
<tr>
<td>Comprehensive transfer functions</td>
<td>describes heat flows in building elements, combining individual wall transfer functions for an enclosure</td>
<td>[33]</td>
</tr>
<tr>
<td>Conduction transfer functions</td>
<td>expresses the decay of temperature through the material</td>
<td>[31]</td>
</tr>
<tr>
<td>Cooling load temperature difference</td>
<td>includes the effect of time lag in the propagation of heat through the material, due to thermal storage</td>
<td>[19]</td>
</tr>
<tr>
<td>Diurnal heat capacity</td>
<td>measures the effectiveness of the material for heat storage during a continuous 24 h cycle</td>
<td>[28]</td>
</tr>
<tr>
<td>Effective heat capacity</td>
<td>accounts for the effects of the building's materials' thermal properties and design factors on the long term energy performance</td>
<td>[29]</td>
</tr>
<tr>
<td>Effective heat storage</td>
<td>accounts for the effects of thermal capacity and thermal resistance of the building elements, and the exterior resistance, for exterior and interior building elements</td>
<td>[38]</td>
</tr>
<tr>
<td>Envelope heat transfer coefficient</td>
<td>includes the effects of thermal transmittance of the material along with heat transfer rate due to infiltration</td>
<td>[17]</td>
</tr>
<tr>
<td>Heat capacity</td>
<td>introduces the effect of heat storage for different building types in the correlation coefficients used in calculating the solar saving fraction</td>
<td>[36]</td>
</tr>
<tr>
<td>Mass effect coefficient</td>
<td>accounts for the temperature fluctuation allowable in the space, the amount of heat gain due to ambient conditions, and the degree of exposure of the space to ambient conditions</td>
<td>[24]</td>
</tr>
<tr>
<td>M Factor</td>
<td>corrects steady state U values for the building materials</td>
<td>[26]</td>
</tr>
<tr>
<td>Solar saving fraction</td>
<td>correlation coefficients as a function of the heat capacity for specific building types</td>
<td>[36]</td>
</tr>
<tr>
<td>Thermal capacity</td>
<td>determines the heat flow in unit time by conduction through unit thickness of a unit area material, across unit temperature gradient, defined as the product of density by specific heat</td>
<td></td>
</tr>
<tr>
<td>Thermal effusivity</td>
<td>accounts for the response of a surface temperature to a change of the heat flow density at the surface</td>
<td>[37]</td>
</tr>
<tr>
<td>Total thermal time constant</td>
<td>the heat stored in a whole enclosure per unit of heat transmitted to or from the outside through the elements surrounding the enclosure and by ventilation</td>
<td>[30]</td>
</tr>
</tbody>
</table>

Dimensionless correction factor, not a direct measure of thermal storage or insulation capacity of walls.

The model of Givoni [27] and Balcomb and Jones [7] utilizes the concept of heat capacity, the product of density by specific heat, of building materials. The model distinguishes between direct and indirect gains in thermal mass, by using the diurnal heat capacity (dhc) and the total heat capacity (thc). The dhc, introduced by Balcomb and Douglas [28], is a measure of material heat storage effectiveness during a continuous 24 h cycle, while the measures the total heat stored...
if all the material was uniformly raised in temperature. In the Givoni–Balaras model a similar parameter called the effective heat capacity (ehc) is introduced to predict the effects of material properties (density, thermal conductivity and specific heat) and design factors such as the surface area, thickness and location of the structural storage elements, on the long term energy performance of a passive solar system. The model has been validated with results obtained from other models and can predict satisfactorily the performance of direct gain buildings.

The effective heat capacity and a generalized solar load ratio correlation have also been used in a method developed by Wray and Best [29]. The effective heat capacity is first defined empirically, by calculating the quantity that best correlates with auxiliary energy consumption, and then new solar load ratio correlations are established, that contain the resulting effective heat capacity as the single variable pertaining to thermal storage. This work confirms the hypothesis by Givoni that ehc resembles dhc, but has no optimum relative to thickness, for a fixed area.

Givoni and Hoffman [30] extended the use of the thermal time constant (TTC) concept for an enclosure, by introducing the total thermal time constant of the building (TTTCB), for measuring the ability of the enclosure’s interior mass to admit and store heat. Originally, TTC was derived from the analogy between the heat flow through the building’s materials represented by a thermal circuit and the time constant of an electric circuit, as a single parameter that can be used for evaluating the thermal performance of a building. The TTTCB is defined as the heat stored in the whole enclosure, including internal air, per unit of heat transmitted to or from the outside through the elements surrounding the enclosure and by ventilation. The shorter the TTTCB, the smaller the heat flux needed to achieve a unit variation of temperature. The method calculates internal air temperature and has been validated for different model building materials and geometries, under natural climatic conditions and with full-scale buildings in different climatic zones [30].

Kusuda [31] has developed a model based on the response factor method (RFM) [32]. It utilizes the conduction transfer functions (CTF), which is a convenient and effective tool for the evaluation of transient heat transfer through building construction components. The RFM and CTF methods are used in building simulation programs to solve transient heat transfer problems in which the heat transfer properties are time-invariant. The advantage of these methods is that they are more efficient than other classical techniques for solving long-term heat transfer problems like Euler or Crank-Nicolson, because there is no critical time step and the internal temperature distribution is not calculated [33]. The RFM has also been used by Stephenson and Mitalas [34] for one-dimensional problems. An exact set of transfer functions and/or response factors is determined by solving the conduction equation by Laplace and/or z-transforms. Ceylan and Myers [35] have presented a method for calculating transfer functions for multi-dimensional heat transfer from a set of first-order differential equations, which requires the calculation of eigenvalues and eigenvectors of a matrix. Seem et al [33] have improved the last method, by eliminating the intermediate steps, thus providing a simple computational and accurate two- or three-dimensional heat transfer calculation. The basic heat transfer process that occurs in a building zone is illustrated by an electrical circuit network. The heat transfer system is then solved in the zone temperature or the zone load calculation modes. The Kusuda model has been used for a study of various types of buildings. The cooling requirements of the buildings studied in this series averaged 22% less for heavier constructions.

Researchers at the Los Alamos National Laboratory (LANL) have published numerous data on tests they have conducted on passive test cells, along with various correlations which were developed using a mainframe computer program (Passive Solar Energy code, PASOLE). The use of the LANL model, however, is limited due to the fact that it is applicable only to buildings similar in their heat capacity, type of glazing or night insulation, to the types specified by the model. The model utilizes the solar saving fraction [36] which depends on the building’s thermal storage capacity, nominal mass thickness, mass to glazing area ratio, number of glazing and night insulation conditions.

van der Maas and Roulet [37] have developed a model for simple energy calculations of stack ventilative night cooling in a building zone, with an air-entrance and air-exit opening. The algorithm links stack ventilation to heat transfer and a wall thermal model and predicts the influence of building materials and opening sizes on the heat transferred out of one zone by nighttime ventilative cooling. The heat transfer processes are represented by a thermal network. The method introduces the thermal effusivity of building materials (the square root of the product of density, specific heat and thermal conductivity) which accounts for the response of the surface temperature to a change of the heat flow density at the surface. The model has been validated with measurements collected during tests conducted in office rooms ventilated by a single open window, and a test at a high mass, three level, staircase in an office building, cooled by stack ventilation.

Mathews and Richards [38,39] have developed a model for thermal simulation of a building zone. It predicts hourly air temperatures and sensible energy loads and treats the effects of heat storage. The proposed approach introduces a novel treatment of heat storage in buildings and a term describing varying ventilation rates. The relevant equations are solved under the assumption that all variables are periodic. The thermal network for a single building zone includes the time-dependent radiative heat source acting on the internal structure, the solar temperature acting on the exterior, the convective heat source acting on the internal air volume, and the outdoor temperature acting on the internal air volume. The method uses a single zone approach and consequently no heat exchange exists between different zones in a building. The air temperature distribution throughout the zone is assumed uniform. All interior surfaces are assumed to be at
the same temperature. The model has been extensively verified in more than 60 passive, naturally ventilated buildings [40]. For 80% of the time temperature predictions were within 2 °C of measurements, showing that heat storage effects are efficiently simulated.

Passport Plus [41] is a simplified computational tool, for DOS compatible micro-computers, developed within the CEC Research Programme on passive cooling in buildings, PASCOOL [42]. The program is structured in such a way as to easily accept enhancements and modifications, in the form of a routine that treats specific phenomena. Some of the program’s features include a more detailed treatment of the thermal mass problem based on transfer functions and finite differences, accounting for the role of the building’s surrounding external environment, small scale micro climate, external remote obstacles, external shading devices like louvres, and improved treatment of natural ventilation phenomena. The program handles multi-zone buildings, including active and inactive zones, using hourly input meteorological files. Passport Plus calculates indoor air and wall temperatures, indoor air flows, cooling or heating loads and indoor thermal comfort conditions. The program has undergone an intermodel comparison between several well-known models and with experimental data from several European sites, with satisfactory results.

Givoni [36] has developed a new predictive model for direct gain (PMDG), to replace the constants of the LANL model with functions dependent upon the thermal properties of the building, the components of the solar system, or both. The modified LANL model can be used for buildings with any heat capacity, down to a lower limit of 150 Wh/m² °C. Based on an experimental study and a comparison between the PMDG and LANL models with the collected data, it appears that the LANL model can be used even for buildings that do not have the exact properties of the reference buildings, although the PMDG model may provide a more accurate prediction of the auxiliary load.

Seem et al. [33] have developed a model which utilizes the TFM procedures for computing the cooling loads and floating room temperatures in buildings. The transfer functions describing heat flows in building elements are combined in a comprehensive room transfer function (CRTF) for an enclosure. CRTF simulations require less computational effort than energy balance simulations because only outputs of interest are computed. The method accurately models longwave radiation exchange and convection in an enclosure through an approximate network, called the ‘star’ network. Resistances in the star network are determined from a network which uses view factors to model long wave radiation exchange. Combining heat flows from every surface to the star nodes results in the CRTF equation, which relates the load for an enclosure to past and current inputs and past loads.

The Shaviv model [43,44] is a time-dependent method which simultaneously solves the heat transfer equation through all exterior walls of the building, taking into account the thermal mass of exterior walls and partitions. The internal thermal mass is treated as an isothermal mass. The model calculates the maximum indoor air temperature, without any mechanical means, or with a fan only. A series of simulations using this model has shown that the optimum thickness of a concrete layer of an internal partition should be 10 cm, while the recommended thickness of an external wall is 15 cm [45].

SPIEL [46] is a simplified design tool for buildings which can calculate the mean monthly hourly indoor temperature and required backup heating or cooling to reach the set indoor air temperature. This approach does not allow for a distinction between direct or indirect thermal gain mass, thus it is not possible to optimize the location of the mass. Thermal mass effects are taken into account by the capacitance of the building, that is, its ability to store heat. The model can handle multi-zone buildings, it accounts for internal heat gains, natural and forced ventilation, and indirectly for night ventilation. A new version of the program, recently released, has improved its many features.

Finally, according to the simple steady-state model [17], when buildings are exposed to hot summer weather conditions for which both the day and night outdoor temperatures are sufficiently warm to cause a 24 h continuous net positive space cooling load to exist, the average daily space cooling load can be calculated by the steady-state theory. This relation is the product of the envelope heat transfer coefficient and the temperature difference of the average outdoor temperature and a balance point temperature which is the average daily outdoor temperature at which the daily space cooling load vanishes.

Simplified design tools offer an alternative to more advanced and complex programs which are also available. Advanced models require a great amount of input information and provide in return the capability for treating complicated phenomena with high accuracy. Advanced programs are suitable for simulating the behaviour of buildings and evaluating the performance of various systems with great accuracy. They are more likely to be used by people with advanced knowledge on these subjects, for scientific and research activities.

There are several advanced computer models for simulating the thermal behaviour of buildings, like DOE [47], TARP [48] and BLAST [49]. Several European research programmes in the area of energy conservation in buildings, have utilized extensively the environmental systems performance (ESP) software [50,51]. TRNSYS [52] has also been a very popular commercially available program in the field of solar energy system design, mainly because of its modularity, especially following the release of a version for personal computers.

5. Conclusions

The mass structure plays an essential part in the thermal response of buildings. Generally, a high mass building has a smaller interior air temperature variation than a low mass building, while there is a decrease and a time lag of the peak
cooling load. For locations with large diurnal temperature swings, this process can significantly reduce the energy consumption of the mechanical cooling system. This technique is more applicable to offices and other buildings which are unoccupied during the night, so that the structure can be cooled with nighttime ventilation. Air-conditioned buildings can also be precooled during off-peak hours, for considerable energy savings. Resulting small indoor temperature variations have also a positive influence on occupant thermal comfort.

For the designer, the primary objective is to calculate the optimum thermal mass of a building and to then distribute it in such a way as to optimize temperature fluctuations and heat return rate into the indoor environment. Material selection is also important, since thermophysical properties influence the overall performance of heat storage systems.

The evolution of cooling load and energy calculations from the crude whole building approximations 30 years ago to the current sophisticated analysis offered by many commercially available programs has been overwhelming [53]. Amongst the several available design tools, for cooling load calculations, the user has to select one based on specific criteria for a given application. Depending on the features of a model, available information and desired accuracy, one can identify the most appropriate tool for practical applications or a more in-depth analysis.

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References

[40] Quick, a thermal analysis program, Version 4, Centre for Experimental and Numerical Thermalflow, Department of Mechanical Engineering, University of Pretoria, Republic of South Africa, 1991.
NBSIR 83-2655, National Bureau of Standards, Gaithersburg, MD, 
1983.

Thermodynamics Program, Vol. 1, User’s Manual, Rep. CERL-
TR-E-153, US Army Construction Engineers Research Laboratory, 
1979.

[50] J. Clarke, Energy Simulation in Building Design, Adam Hilger, Bristol, 


[52] S. Klein, TRANSYS, a transient system simulation program, Rep. JR-
12, Engineering Experiment Station, University of Wisconsin-