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Thermal inertia in buildings: a review of impacts across climate and building use

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ABSTRACT

A building with a great amount of thermal mass is able to time-shift and flatten out heat flow fluctuations; this is referred to as the thermal inertia of a building. This paper presents a literature review focussing on the reported impacts of building thermal inertia on thermal comfort and energy use for space heating and cooling. A wide range in research methods, building types and climatic conditions considered by the respective authors, contributes to a large spread in research outcomes. As a general tendency it can be concluded that for most buildings and climates, higher amounts of thermal mass at the inner side of the thermal insulation appear to be beneficial with regard to improving thermal comfort and reducing the energy demand. The impact on energy demand is however relatively small. With an order of magnitude of a few percent for most cases, other design parameters such as thermal insulation of the building envelope and solar heat gains will be more significant. The paper reviews some practical applications exploiting the effect of thermal inertia in design and operation of HVAC systems, and concludes with a discussion on the apparent discrepancy in simulation outcomes and suggestions for further research.

Keywords

Thermal inertia; Dynamic heat transfer; Thermal mass; Specific heat; Heat capacity; Overheating; Thermal comfort

Nomenclature

A	Surface area [m²]
b	Thermal effusivity [W m^{-2} K^{-1} s$^{-1/2}$]
c	Specific heat capacity [J kg^{-1} K^{-1}]
c_a	Specific heat capacity of air [J kg^{-1} K^{-1}]
C	Volumetric heat capacity [J m^{-3} K^{-1}]
C_{eff}	Effective thermal capacitance [J m^{-3} K^{-1}]
C_v	Ventilation conductance [W K^{-1}]
d	Thickness of a material slab [m]
f	Decrement factor [-]
f_r	Thermal response factor [-]
M	Thermal mass of a building [kg]

N	Room air change rate per hour [ach]
q_c	Conductive heat flow [$m^3 s^{-1}$]
q_v	Ventilation rate [$m^3 s^{-1}$]
R	Thermal resistance [m^2 K W^{-1}]
T	Temperature [K]
t	Time [s]
T_i	Average indoor air temperature [K]
T_D	Decrement factor [-]
T_o	Outdoor air temperature [K]
U	Thermal transmittance [W m^{-2} K^{-1}]
V	Room volume [m^3]
x	Space-coordinate [m]

Greek letters

a	Thermal diffusivity [m^2 s^{-1}]
δ	Periodic penetration depth [m]
ζ	Amplitude reduction factor [-]
λ	Thermal conductivity [W $m^{-1} K^{-1}$]
ρ	Density [kg m^{-3}]
τ	Time constant [s]
Y	Thermal admittance [W m^{-2} K^{-1}]

Abbreviations

BEPS	Building Energy Performance Simulation
BREEAM	Building Research Establishment Environmental Assessment Method
CTF	Conduction Transfer Function
DOE	Design of Experiments
DSM	Demand Side Management
DBMS	Dynamic Benefit for Massive Systems
EPBD	Energy Performance of Buildings Directive
HATS	Hybrid Adaptable Thermal Storage
HQE	Haute Qualité Environnementale

HVAC	Heating, Ventilation and Air Conditioning
IAQ	Indoor Air Quality
KPI	Key Performance Indicators
LEED	Leadership in Energy and Environmental Design
MPC	Model Predictive Control
PCM	Phase Change Material
PV	Photo-voltaic
TABS	Thermally Activated Building Systems
TES	Thermal Energy Storage
TFM	Transfer Function Method
TOU	Time of Use
TSBM	Thermal Storage in Building Mass

1 INTRODUCTION

Energy consumed in residential and commercial buildings increases by an average of 1.5% / year, and accounts for 20.1% of the globally delivered energy in 2016.[1] The most important share of this energy demand can be attributed to the heating, ventilation and air-conditioning (HVAC) systems which regulate the indoor thermal comfort and indoor air quality (IAQ). [2] Two main strategies can be distinguished to improve building energy efficiency.[3] Active strategies encompass improvements to heating, ventilation and air conditioning (HVAC) systems and artificial lighting, whereas passive strategies involve improvements to the building envelope such as increasing thermal insulation and optimizing solar gains to lower the energy demand of a building.

Increasing the thermal resistance of the building envelope by applying thermal insulation materials is generally advocated as the most crucial factor to reduce the building energy demand, especially in heating dominated climates. [4] Consequently, many energy performance rating schemes and code standards set specific requirements to the thermal resistance (R-value) or thermal transmittance (U-value) of building components.[5] These performance indicators relate to the one-dimensional steady state thermal conduction of building envelope components such as walls, roofs and floors. R-values and U-values are simplified representations of the heat transfer of a building envelope component, as these indicators do not factor in any dynamic behaviour. The latter is introduced by exposing a building to variations in usage and environmental conditions such as time-varying outdoor temperature and solar irradiation.

In a transient situation, the thermal mass of a building can absorb, store and progressively release heat depending on the temperature difference with the immediate surroundings. The amount of heat stored depends on the density ρ and specific heat capacity c of the material, whereas the rate of heat exchange is influenced by the thermal conductivity λ of the material. Buildings with a large amount of thermal mass within the thermal envelope, will display a reduced and delayed reaction to an initial excitation such as a sudden rise in external ambient temperature. This transient behaviour is referred to as the thermal inertia of a building.

Building thermal inertia is a complex phenomenon, which is not always fully understood by design practitioners. As part of ‘climate responsive architectural design’ or ‘passive solar design’, architects and researchers have often argued that thermal mass is beneficial for maintaining indoor thermal comfort and reducing energy demand. [6–10] Indeed, constructing methods with a high amount of thermal mass - often obtained by using large quantities of concrete or bricks - have proven to be beneficial for reducing overheating risks in numerous case studies. [11–16] This behaviour can be witnessed in buildings with large amounts of exposed thermal mass such as medieval churches, which display very slow fluctuations in indoor temperature, and thus remain cool during a hot week in summer, without the need for active cooling. This effect is also exploited in many instances of vernacular architecture in hot climates, and in 'rammed earth buildings' and 'earthships' which use large quantities of soil to create a stable indoor climate. [17–19]

Thermal mass isn't always beneficial with regard to comfort and energy consumption. Slee et al. concluded that "the general view that 'mass is good, therefore more mass must be better' is erroneous". [20] An exponential relationship between the quantity of thermal capacity and the internal diurnal temperature fluctuations implies that adding additional thermal mass to a heavy weight building has a negligible effect. Furthermore, buildings with large amount of thermal mass need more time to reach the cooling or heating set point temperature in case of intermittent building use. This might cause thermal discomfort for occupants and result in an increased energy consumption due to longer preheating or precooling periods. [21,22]

It can be concluded that estimating the effect of thermal inertia on building energy consumption and thermal comfort is not always self-evident. The subject has been studied widely by many authors, but the research methods and scope of the various studies differ greatly. An early example of an analytical approach is described in the report 'Thermal mass assessment' by Childs et al. [23]. Many other authors have instead relied on measurements or advanced computer simulations. Thermal inertia is a complex phenomenon, and its relative impact is proven to be influenced by many factors including the climate where the building is located [24], the thermal insulation of the building envelope [25,26], and the type of building usage [15,27]. Thermal inertia is just one of the many factors to consider in a building design, and many authors have described it as part of a wider analysis. Heier et al. provides an in depth overview of the topic of Thermal Energy Storage (TES) in buildings. [28] A distinction is made between passive storage and active storage, which makes use of pumps or fans to charge or discharge the energy storage. The effects of sensible energy storage in building thermal mass are discussed alongside latent thermal mass effects, sensible and latent storage in HVAC systems and storage in direct vicinity to buildings such as borehole energy storage. Olsthoorn et al. provide a review on the specific topic of using thermal mass for peak shaving and shifting of electrical power consumption. [29]

This paper will review the current body of knowledge on the effects of thermal inertia in buildings, and focus on the sensible heat storage and its effects on thermal comfort and energy consumption for heating and cooling. Firstly a description of the qualitative effect and the underlying physical processes is briefly introduced, followed by an overview of the terminology used in literature to describe the effect. The next section describes the modelling methods which are available to analyse dynamic heat transfer, and discusses the modelling approaches of many mandatory energy performance assessments. The main part of the paper focusses on summarising the reported impacts of thermal inertia analysed on the scale of individual construction components and whole buildings. Specific attention is given to the practical application of thermal inertia in building design to enhance its operation. This review paper concludes with a discussion on the factors that can attribute to the large spread in research findings reported in scientific literature and provides suggestions for future study.

2 DESCRIBING AND QUANTIFYING BUILDING THERMAL INERTIA

2.1 Qualitative description of thermal inertia effect

Building thermal behaviour and the related energy consumption are defined by a complex interaction of heat gains, losses and storage in building materials and finishing. Four main sources of heat fluxes can be observed when studying the heat balance of a building. For reasons of simplification, a single room with uniform air temperature will be considered in the following qualitative analysis.

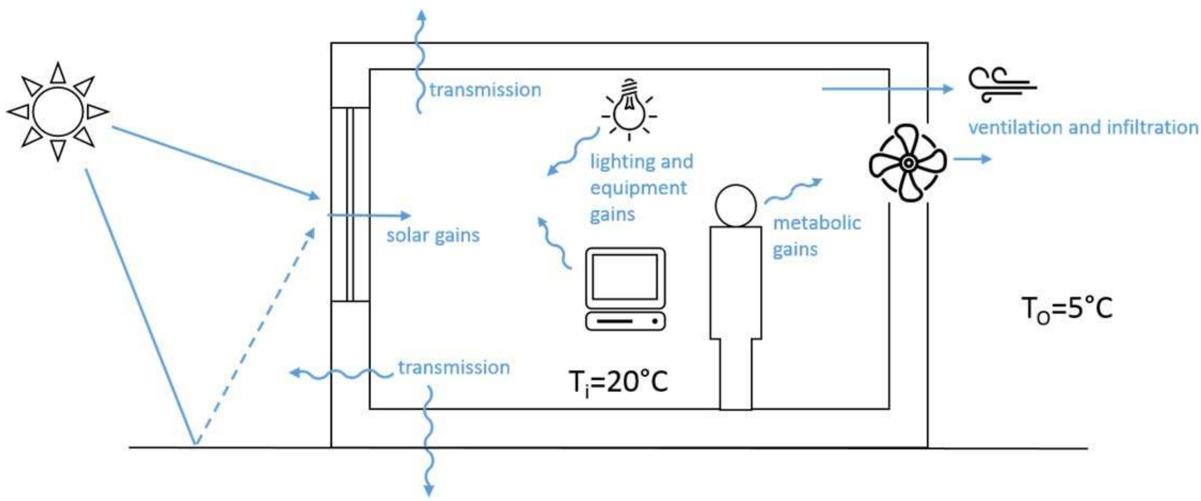

Fig. 1 Schematic overview of heat fluxes to and from a single-room building

The first major heat flux consists of heat generated or extracted internally due to building operations. These thermal loads stem from heat losses from various sources such as artificial lighting, office equipment and metabolic heat gains from building occupants.

Secondly air movement will introduce outside air by ventilation and infiltration through the building skin. If the air pressure remains constant, and equal amount of air is expelled from the building. In case the temperature of the outside air differs from the indoor air temperature, a heat flux is associated with this air movement. This is referred to as convective heat gains or heat losses.

A third heat flux to consider is the direct heat gain which originates from solar radiation transmitted through the transparent components of the building skin such as windows and skylights.

The last main contributor to the heat balance of a building is the heat flow through the opaque building envelope. These transmission losses or gains can mainly be described by the physical process of conductive heat transfer through the materials, although the heat exchange at the inner and outer surfaces and within voids and cavities is based on the principles of convection and radiation.

The aforementioned heat fluxes are the main driving forces which define the heat balance of the room. In order to obtain comfortable indoor thermal comfort conditions, dedicated technical systems such as heating and cooling units can add or remove heat to restore the room's heat balance to an equilibrium, hence maintain a constant indoor temperature.

Many of the boundary conditions inducing these heat fluxes are not constant over time. Weather conditions such as outside air temperature and solar irradiation are constantly fluctuating. In most cases the building operation also imposes fluctuating internal heat loads. Whilst solar radiation and convective heat flows vary simultaneously with the fluctuation of the outdoor boundary conditions, the conductive heat flows through the building skin will display a time lag compared to the external excitation. Heat gains through glazing or from internal activities will raise the indoor temperature, and the internal temperature fluctuations will in turn affect the net conduction, ventilation and radiative heat flow to and from a room. Some of the heat entering the material will be absorbed and stored inside the construction assembly, and as a consequence the temperature of these materials will slightly rise. The peak value of heat flux which is transmitted into the room through conduction is thus reduced and phased out compared to the initial excitation as depicted in Fig. 2.

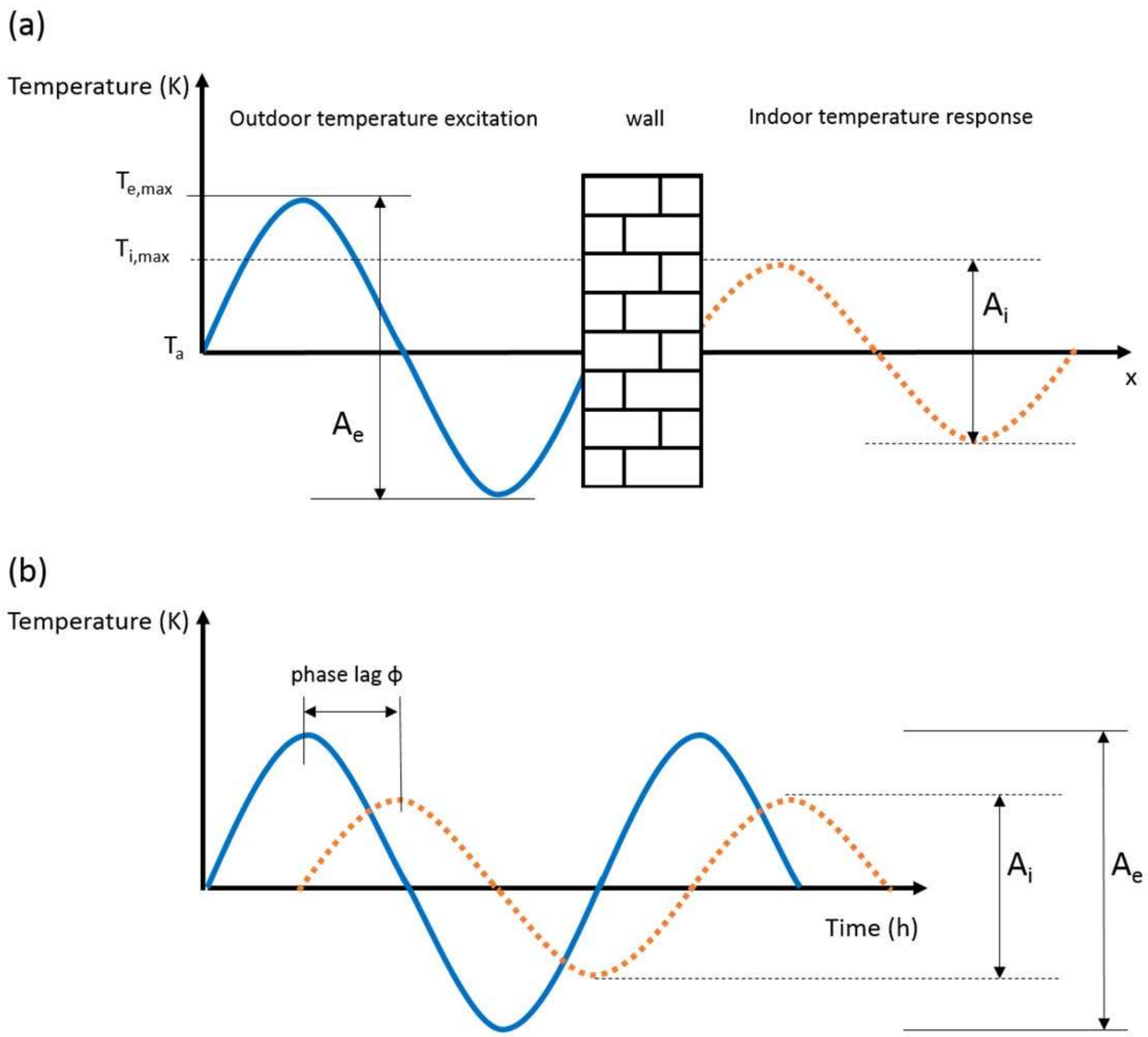

Fig. 2 - Thermal response on a sinusoidal heat wave propagating through a wall

The amount of peak flux reduction and phase shifting is depending on the thermo-physical properties of the materials of the construction assembly. One of the key factors is the mass of the components, hence the designation 'thermal mass effect'. Depending on the thermo-physical properties and thickness of opaque wall elements, approximately 12 hour time lag values can be observed. [30] A very well insulated building (U=0.1 W/m²K) of heavy construction with heat recovery ventilation is even postulated to 'survive' 0°C external temperatures for one week without requiring supplementary heating. [31] There are many similarities to the effect of motion inertia of physical objects -which is the resistance of an object to any change in its state of motion- hence the denomination 'thermal inertia'. The thermal storage material is typically contained in walls, partitions, ceilings and floors of the building, constructed of material with high heat capacity, such as concrete, bricks and tiles. [32]

By introducing transient heat storage and release behaviour, the thermal inertia of a building can help to reduce overheating risks and cooling loads during summer. In particular incident solar radiation and time varying ambient temperature are considered as important driving factors defining the level of air conditioning load in a building. [33] In intermediate seasons, the thermal inertia can assist in creating favourable indoor thermal comfort conditions without the need for active cooling and heating. This is referred to as 'passive' temperature control, as opposed to active systems which consume energy to heat or cool down a building. Especially in climates with high diurnal temperature fluctuations, the thermal inertia of a building can have significant impact on the heat fluxes. Heavy structures such as masonry walls may be up to 60% more effective in retarding heat flow than steady state U-values would indicate. [15]

The thermal inertia effect can also directly influence the heating and cooling demand of a building, and the resulting energy consumption. Because of the dynamic interactions, the time of occurrence of heat gains or losses will affect the total energy consumption of a building in an unsteady regime. Depending on the amount of heat already stored in building components, additional heat gains could either assist in reducing the energy consumption by limiting the additional demand for space heating to be delivered by the HVAC system, or conversely increase the consumption resulting from higher cooling demands.

Thermal inertia could also have adverse effects on the thermal comfort of occupants, as it will take more time to reach the desired indoor temperature during intermittent building operated. Even if the air temperature is at the desired comfort temperature, the radiant heat exchange with slow reacting colder or hotter internal surfaces might cause discomfort to people. Occupants might anticipate on the large time lags of a building with a high thermal inertia, and adapt the timing of heating or cooling thermostat set points accordingly to avoid thermal discomfort. This preheating or precooling the building ahead of occupancy will lead to an increase in energy demand. For buildings with short usage periods and a high amount of thermal inertia alternative heating systems could be more appropriate, such as radiant heating systems, or specific solutions such as local heating systems integrated into church benches. [34]

The analysis above was restricted to one single room. In reality buildings are more complex, often containing rooms at different average temperatures whilst air and surface temperatures are generally not uniform within one single room. Internal partitions and furniture also contribute to the overall thermal mass available to store and release heat.

2.2 Physical processes defining thermal conductance in building components

Thermal storage in buildings can rely on either sensible heat storage in which the temperature of a material changes, or latent heat storage using phase change materials. This paper focusses on sensible heat storage in building thermal mass, which is the most common application. Latent heat storage is briefly introduced as part of the specific applications of building thermal inertia in a later section.

The physical processes by which heat transfer takes places in a building are thermal conduction, convection and radiation, and to a lesser extend latent heat transfer. [35]

Heat transfer by conduction is governed by Fourier's law.

$$\rho c \frac{\delta T}{\delta t} = \lambda \frac{\delta^2 T}{\delta x^2}$$

If the temperature on both sides of a building component remains stable for a long period of time, the heat flux through a construction will attain a constant value. For a one-dimensional heat flow in a homogeneous material and in a steady state situation, the temperature gradient over the construction will be linear. Under these specific circumstances the conductive heat flow can be expressed as

$$q_c = U\Delta T = \frac{1}{R}\Delta T$$

Charactering the thermal properties of a building envelope component by its thermal resistance *R* or thermal transmittance *U* has become custom in building engineering practice and many standards and building codes.[5] It should be noted that by definition, these properties are only valid for situations of one-dimensional steady state conduction.[36] Although the thermal conductance and thermal resistance of constructions can be depended on factors such as temperature and humidity, they are mostly considered constant for practical applications. [37,38]

The expression of 'heat flow through a wall' does not have a clear meaning in the case of transient heat flow, as the heat flow will be dependent on the position in the wall. [23] The effect of thermal inertia is not revealed by a steady state analysis, which solely assesses the thermal transmittance (U-value) of the external building surfaces. In an actual building the surface temperature varies continuously, and seldom, if ever, are steady-state conditions established. Time dependency is caused by ever changing boundary conditions of external temperature, solar irradiation and internal heat load. Heat transfer in this situation is referred to as “dynamic heat transfer”.[23]

2.3 Terminology to describe thermal inertia

In literature no uniform definition is used to define the effect of thermal mass on the thermal behaviour of a building.

Guglielmini et al introduce the term ‘passive thermoregulation effect’, to describe the effect that building thermal inertia is able to reduce the fluctuations of the inside air temperature. [39]

The terminology ‘*thermal inertia’* appears to be used by many authors, but lacks a formal definition and physical properties to describe it. Online dictionary Merriam Webster describes thermal inertia as ‘ the degree of slowness with which the temperature of a body approaches that of its surrounding and which is dependent upon its absorptivity, its specific heat, its thermal conductivity, its dimensions, and other factors’ [40] This term is a reference to the concept of motion inertia of a physical object, which is defined as resistance of any object to a change in state of motion.

In earth sciences, thermal inertia is defined as “The resistance of a material to temperature change, indicated by the time dependent variations in temperature during a full heating/cooling cycle (a 24-hour day for Earth)”.

Another definition found in literature defines thermal inertia as ‘a process of the inertial space and wall system in which an external heat source causes a gradual rise in the temperature distribution until an equilibrium state is reached’. [30] Kontoleon and Bikas define thermal inertia as the rate of heat absorption or rejection. [41] This definition is incomplete as is lacks to encompass the actual storage capacity of a building or building component.

Many authors use the terminology ‘thermal mass’, especially in the non-scientific literature. Knowledge of the thermal mass is however not sufficient to describe the transient behaviour of building components. This parameter fails to describe the thermal conduction which defines the speed of heat storage and release processed. Furthermore it does not incorporate the distribution of the thermal capacities in a multi-layered construction component. Aste et. al provide some examples of how structures with the same thermal mass can have significantly different values of thermal inertia related properties such as decrement factor and thermal phase lag. [26] Additionally, the wording ‘thermal mass’ only refers to sensible heat storage, whereas latent heat storage using phase change materials can also attribute to the thermal inertia of a building without using large quantities of building materials with a high heat capacity. Similarly, the widely used terminology ‘heavy’ or ‘massive’ and ‘light’ to describe construction types should be used with caution. A heavy construction with thermal insulation at the inside can behave similar to a lightweight construction, and conversely lightweight construction components with latent heat storage can perform similar to heavy weight constructions. [11,42]

Other terminology found in literature includes:

- Thermally heavy buildings [22]
- Thermal flywheel effect [43]
- Sensible thermal energy storage [22]
- Transient conduction effect [44]
- Thermal storage in building mass (TSBM) [45]
- Dynamic benefit for massive systems (DBMS) [46]

Additional parameters and properties which are used to quantify the thermal inertia of a building or building component are discussed in the annex of this paper.

2.4 Modelling thermal inertia

In-situ measuring the impact of thermal mass on energy consumption and indoor thermal comfort in occupied buildings would be a tedious and expensive undertaking, although some large scale experiments have been reported. [47–49] In analysing measurements data, it is difficult to distinguish the impact of the thermal inertia from other influencing parameters such as local climatic conditions and user behaviour. Instead of measurement campaigns, most authors have opted for theoretical models and simulations. This approach uses a physics based formulation to describe the dynamic behaviour of heat conduction, storage and release, allows to analyse and compare many building variants without the limitations related to measurement setups. Accurately modelling the effect of thermal inertia requires solving the differential algebraic equations for time dependent heat transport [50]. Before the advent of relatively user friendly BEPS tools, many attempts of analytically or semi-numerically solving these equations for simplified conditions are described in literature. [39] The analytical approaches have the benefit of providing an exact solution, but an important limitation is that they can only be applied for simplified cases and boundary conditions. Advanced user behaviour such as opening of windows, or HVAC system operations cannot be modelled. As an example, most researchers using analytical techniques implement sinusoidal boundary conditions as a first order approximation of the real world diurnal outdoor air temperature variations. [15,51–53] Some analytical approaches add Fourier analysis to describe the temperature profile as a sum of sinusoidal components, but this is still not reflecting the actual complexity of time varying outdoor temperature and incident solar radiation. [54]

Due to the similarity in the mathematical description of heat transport and electrical currents, an analogue technique known as the electrical network analogy or circuit modelling has also been used to model the transient thermal behaviour of building components. Using such a setup, electrical resistors mimic the behaviour of thermal resistance (R), and the thermal mass of a building is represented by a capacitor (C). [55,56] Even nowadays lumped parameter thermal network models using RC analogies are used in practice, although their analogue setup has been replaced by computerized solving of the RC network. [56–58]

Computational building performance simulation is an area of investigation since the 1960s. [59] Numerical solvers are implemented in software code to provide an approximate model of the building and its subsystems. Many commercial and open domain simulation software suites are available, which integrate the simulation of a wide range of physical phenomena including thermodynamics of the building skin, HVAC system modelling, daylight and solar heat gain modelling and airflow models. With the advent of computerized BEPS, the thermal response factor method was developed in 1967 by Stephenson and Mitalas. [60] Using this approach, the dynamic thermal characteristics of the building are expressed by the set of system response factors, which allow for rapid computer calculation of the thermal loads and indoor temperature evolution of a building. [61] Other tools deploy frequency response methods, which are also called harmonic methods. [62] Dynamic building simulation codes in use nowadays often base their calculations on the Transfer Function Method (TFM), which is also referred to as conduction transfer function (CTF) method. [63] Although this method is generally accepted in BEPS practice, some authors have concluded that the TFM results may not be considered reliable starting from thicknesses larger than 60 cm. [26] Luo et al. propose to use a modified CTF method which uses a higher order discretization scheme for the surface heat flux as well as finer grids at the layer boundaries for multi-layer constructions to increase the accuracy. [64] For specific applications, finite volume or finite difference methods are used in BEPS to numerically solve the heat transfer equations, although this comes at the expense of greater computation time. [65,66]

Many BEPS tools used in building practice and academia are validated using the BESTEST method, or ANSI/ASHRAE Std-140 which is based on BESTEST [67–70] These testing frameworks are composed of analytical tests with closed form solutions, empirical tests with results based on measured data, and comparative tests. The objective of these testing procedures is to increase confidence in the use of BEPS tools by validating, diagnosing, and improving the software. Kalema et al. have evaluated six BEPS software packages, and concluded that the differences between the simulation models are rather small for heating, although the results for cooling present a larger spread. [47] Differences in input data by different users are causing larger deviations in simulation outputs than the choice of a specific dynamic simulation tool.

Based on literature review it is clear that whole building energy simulations tools are a well-developed and suitable instrument to simulate the transient behaviour of a building model, although some limitations still remain, e.g. the lack of fully incorporating the effect of thermal bridges in dynamic simulations. [71–73] Nowadays analytical or analogue models to assess the effect of dynamic heat transfer have mostly become obsolete. Despite the advanced capabilities and broad availability of dynamic BEPS tools, their use is currently still limited in building design practice, especially for small scale projects. [74] This can be attributed to the steep learning curve, the time and effort needed to operate the software, and the imposed use of simplified steady state calculation tools in building codes, which make the more advanced simulations redundant. The ASHRAE Fundamentals handbook states that steady-state calculations can be used to define the average heating energy demand in cold climates, but whole-building simulations complying with NSI/ASHRAE Standard 140 are recommended in climates where daily temperature swings oscillate around a comfortable mean temperature. The effects on the mutual dependences all factors defining the transient thermal response is "rather complex" and there is no simplified approach that can account for these interactions. [35]

2.5 Thermal inertia in energy performance assessments

The field of energy performance of buildings assessment has received great attention in the last decades, due to economic, political and ecological motives. In many parts of the world programs have been set up to reduce the energy consumption of buildings, both newly constructed as well as part of the existing building stock.[75] This includes voluntary rating schemes as LEED (Leadership in Energy and Environmental Design), BREEAM (Building Research Establishment Environmental Assessment Method), HQE (Haute Qualité Environnementale) as well as legislative initiatives such as the European Union (EU) Energy Performance of Buildings Directive (EPBD), of which the 2010 recast requires all new buildings in the EU to consume 'nearly zero' energy after 2020. [76–79] Instead of measuring and analysing actual consumption of a building in operation, most of the building rating schemes impose a calculation routine to calculate the energy efficiency of a building as a whole, or impose targets on individual components, such as the thermal resistance of the building envelope or the energy efficiency of HVAC equipment. [80–82]

Calculation methods and dedicated simulation software assist the building designer to estimate the energy consumption during the design phase of a building. These tools allow to test the effect of design iterations taking into account building properties such as massing, HVAC systems, window properties, thermo-physical properties of the building envelope, etc. Although mainly aimed at new constructions, such software tools are equally suited to assist in choosing optimal building retrofit strategies. To assist designers and building engineers in these tasks, a plethora of energy performance analysis tools is available nowadays, both commercial and open source [74,83]. The building energy performance calculation methods can be structured in two main categories: simplified steady-state calculation tools and dynamic simulations. [84]

The simplified methods such as the monthly calculation method of ISO 13790 are based on a set of algebraic equations which describe steady state energy flows, e.g. by using monthly averaged temperatures for buildings and their surroundings and thermal transmittance described by fixed U-values. [85,86] These simplified methods are often prescribed in building codes, as they allow to impose a set of simple performance criteria and do not require advanced expert knowledge from a user. Another benefit of the (semi-)steady state calculation models is the short simulation time and limited data input, which enables swift design iterations during the early design stages. A major disadvantage of the simplified (semi-)steady state methods is that they fail to accurately represent the dynamics of the heat transfer. This has two significant implications for the use of these tools. Firstly these methods do not allow to calculate detailed time series of the heat fluxes nor of the fluctuations of the indoor air temperature and indoor radiant temperature. As a consequence they are not capable of assessing the thermal comfort in case of free running operation or buildings with restricted HVAC capacities, and they are not suited for sizing the capacities of HVAC systems. Secondly, the simplified methods - e.g. with monthly energy balances - do not allow to incorporate effects of heat storage and release, and time dependency of energy flows, which can cause deviations in the predicted energy use as discussed in the qualitative example. Some of the methods tackle this problem to some extent by introducing a dimensionless gain utilization factor which expresses the approximate share of heat gains that will be effective at reducing the heating demand. [47,87,88] Nevertheless, these methods will only allow a first order approximation of the effect of thermal inertia. [89]

The rapid progress of computer power gave rise to a broader introduction of dynamic building energy simulation tools in the last decades. Several software codes are now capable of simulating solar irradiation, heat transport, heat storage and HVAC systems for whole buildings with short time intervals, thus allowing to evaluate the transient nature of building thermodynamics. [83] The ASHRAE Fundamentals handbook points out that especially in climates where daily temperature swings oscillate around a comfortable mean temperature, transient analysis with whole-building simulations complying with ANSI/ASHRAE Standard 140 is more appropriate. [35] Whole building energy performance simulation (BEPS) tools can be especially supportive when integrated early on in the architectural design process.[90] The dynamic simulation tools allow architects and engineers to optimize a building design and evaluate the potential impact of design alternatives including advanced concepts such as adaptive facades and thermally activated buildings systems. The simulation tools can also be used to assist the control of a building in operation – which commonly referred to as model predictive control (MPC).[91] The dynamic approach offers several advantages over simplified steady-state calculations – especially with regards to the assessment of the effects of thermal inertia. Important drawbacks however are the complexity of learning and operating these tools [74], and a lack of reproducibility and transparency resulting from many subjective modelling assumptions which have to be made. [84] This can explain why many of the building labelling schemes still rely on simplified steady state energy calculations, such as notably the case in the implementation of the EPBD in many of the EU member states which are based on a monthly energy balance method according to ISO 13790:2008. [80,92,93].

3 Impacts of thermal inertia in buildings: literature overview

3.1 Analysis on individual building components

Several authors have evaluated the influence of thermal mass on the thermal behaviour of individual building components. Most studies performing such an analysis have focused the building exterior walls, e.g. by comparing different wall assemblies. Interestingly, based on the body of literature reviewed, the effect of thermal mass of roof assemblies did not appear to receive the same amount of attention as did the study of wall assemblies.

Lindberg et al. performed a rare case of longitudinal in-situ measurements on the effect of thermal inertia. [48] During five years, 520 sensors in each of six test buildings located in Tampere (Finland) gathered data on indoor air temperatures and temperature profiles at various wall depths, as well as the exterior environmental conditions. The authors conclude that non-steady calculations are in good correspondence with the measured data, and underpin that these are essential for accurately representing temperature distributions and heat losses through building envelopes. Tsilingiris derived a numerical model to predict the transient behaviour for a wide range of structural wall designs. [43,94] The results are primarily aimed to be used a basis for peak load control strategies. The wall surface absorptivity which affects the heat exchange by radiation is found to be a key parameter to describe the transient behaviour. In later work the space distribution of wall heat capacity in multi-layered walls was also explicitly taken into account. [95] Ulgen investigated both analytical solutions and experimental data. The latter were gathered using a hot box setup using 1m by 1m wall samples. [30] It is argued that composite types of walls formed by different layers are needed to balance heat storage and heat spreading coefficients. A study of Asan focused especially on how the time lag and decrement factor are affected by the thickness of wall insulation and its position in a wall assembly. [42] The total wall thickness of insulation and thermal mass was considered to be 20 cm for all situations, and the effect of the position of the insulation in the wall is reported. Al-Sanea et al. performed similar analysis to derive optimal properties and layer distribution for insulated walls in the hot climate of Saudi Arabia. [96] It was concluded that the optimum wall assembly has the thermal mass on the inside relative to the thermal insulation layer. Ciampi et al. studied the optimal sequence of layers in non-homogeneous walls in order to minimize the fluctuation of the power needs of the air-conditioning plant. [97] They developed an analytical approach to define a non-dimensional coefficient of performance. For this specific purpose, the ideal wall setup is concluded to be a symmetrical three layer 'lumped' wall in which all of the capacity is concentrated in the centre plane which is covered on both sides with equal slices of wall containing the thermal resistance.

Bojic and Loveday investigated the impact of wall layer composition by simulation of a windowless box located at 51°N with a fixed wall thickness and U-value of 0.142Wm^{-2}K^{-1}. [98] They conclude that in case of intermittent heating a wall with thermal insulation at the inner side provides the best results, with a reduction of up to 40% in daily energy consumption. In the case of intermittent cooling however, a wall assembly composed of masonry/insulation/masonry clearly outperforms other variants, with 80% lower cooling energy demand than a homogeneous wall and 72% lower compared to an insulation/masonry/insulation construction.

Long and Ye study the effect of thermal inertia by investigating a single room with both internal and external walls. [99] They advocate a room can serve as a typical physical representation of a building, overcoming the complexity of having a massive number of building design configuration parameters, including the size, orientation, type of window, window-to-wall ratio, internal loads, schedule, etc. The authors deploy simulation tool 'BuildingEnergy' to model the effect of 2160 types of potential materials with diverse combinations of thermal conductivity λ and volumetric capacity C_V. Their analysis has the benefit of covering a large scope of these technical properties, however many of these combinations of material characteristics do not correspond to typical building materials. The general conclusion of the authors is that for summer application, either a decrease in conductivity or an increase in volumetric heat capacity of the materials causes a reduction in cooling energy consumption. For material combinations with a thermal conductance below 0.25 Wm^{-1}K^{-1}, C_V has a negligible effect on the energy performance according to their analysis. During cold season, the general tendency of how the material properties affect the energy performance is consistent with that in summer, but it can be noted that for $C_V \gtrsim 2000$ kJ/(m3·K) additional volumetric heat capacity has a negligible impact on energy demand. The authors conclude that for external walls a low thermal conductivity has priority on greater C_V values, a trend which is consistent for the three distinct Chines climates analysed. However it should be noted that their analysis is limited to a homogenous single layer wall. Internal walls are evidently less significant to the overall energy performance. Internal walls with a higher thermal conductivity prove to be better performing.

A specific construction assembly which received considerable research interest in the past years are green roofs or vegetated roofs. Because of the amount of substrate used – often in combination with a concrete load bearing construction - they can be expected to contribute significantly to the envelope thermal capacity. Getter et al. conclude that shading from the plant canopy, and cooling by evapotranspiration provide additional benefits over a gravel roof. [100] It should be noted that the thermal effectiveness of the green roof can be strongly dependent on the moisture content of the substrate and the climate in which it is applied. [101]

3.2 Evidence on thermal inertia effects in residential buildings

The previous paragraph highlighted some relevant studies on the thermal inertia effects of individual building components. A significant limitation of these approaches is that they lack to integrate the complexity of real life buildings, in which multiple heat fluxes such as solar gains, metabolic heat gains from occupants, convective heat transfer, etc. will mutually interact. Therefore the next section will discuss the literature on the impact of thermal inertia on a building as a whole. This review paper focusses on two main building typologies which received the greatest attention in the scientific literature on this subject: residential buildings and office buildings. Because of their distinct behaviour, they are discussed separately, starting with the residential buildings.

Most of the authors performed an analysis on a single building design, in which only building envelope composition is left to vary, often in a binary approach of high thermal capacity versus low thermal capacity. Table 1 displays an overview of reviewed sources which have quantified the impacts of thermal inertia, including the Key Performance Indicators (KPI) they have analysed and their main results. Some of these sources are further discussed in the following section. In general it can be concluded that most of the studies report that a residential building with a higher amount of thermal inertia will yield a reduction in operating energy.

Table 1 – Literature summary on effects of thermal inertia in residential buildings

Reference	Methodology	Climate / Geography	KPI	Conclusions and reported savings for building variant with high thermal mass compared to case with low thermal mass
[102]	Literature review of in-situ monitoring	Denmark, USA , UK, Austria, Germany, Sweden	Heating energy	Limited and case study dependent. On overage effect of thermal transmittance 10 times larger.
[103]	Simulations (TSBI3 +EN832+BRIS)	Sweden	Heating energy	14% to 18% reduction in heating energy
[104]	Simulations (TRNSYS 17)	Cyprus	Heating energy; Cooling energy	Heating load reduces 47%, cooling load increases 4.5%
[6]	Simulations ("Energy")	Israel	Maximum indoor temperature	5°C reduction in indoor temperature obtainable by use of night ventilation
[49]	In-situ measurements in 2 test houses	New Zealand	Heating energy; Comfort	Beneficial for comfort; impact on heating energy depending on house design, climate and occupant behaviour
[24]	Simulations (DOE-2.1E)	USA, 6 climatic zones	Heating energy; Cooling energy	2.3% to 11.3% savings (depending on climate) for wall with massive layers at inner side
[105]	Test chamber test	Kenya (Nairobi)	Maximum indoor temperature	Reduction from 33°C to 25.4°C
[106]	In-situ monitoring	Brazil semi-humid climate	Decrement factor	Thermal inertia beneficial, not quantified
[107]	Simulations (ESP-R)	Jersey, Denmark (Copenhagen), UK (Birmingham), France (Paris)	Heating energy; Cooling energy	Matrix of gains, insulation and climate region. For most cases high mass buildings are beneficial
[108]	Simulations (DOE-2)	Italy (Milan, Rome, Palermo)	Heating energy; Cooling energy	Up to 30.7% reduction in predicted heating demand and 10.2% reduction in cooling demand for South oriented building in Rome
[15]	Simulations (AccuRate)	Australia	Decrement factor	Reverse brick veneer results in best comfort
[47]	Simulations (Consolis Energy, IDA-ICE, SciaQPro, TASE, VIP, VTT House model, Maxit)	Sweden	Heating energy; Cooling energy	4% reduction (3 $kWhm^{-2}$) in heating energy and 30–50% reduction (4$kWhm^{-2}$) in cooling energy for basic glazing variants
[109]	In-situ monitoring in 3 buildings	Spain	Heating energy; Comfort	Thermal inertia beneficial, not quantified
[110]	Simulations (EnergyPlus)	Italy (Milan)	Heating energy; Cooling energy	10% heating, 20% cooling savings for higher thermal inertia

[111]	Simulations (based on EN15255)	Latvia	Cooling energy; Decrement factor	1.2% cooling savings
[46]	Simulations (Energy10)	USA: Las Vegas	Heating energy; Cooling energy	Heating load reduces, cooling load increases; not quantified.
[112]	Simulations (Derob-LTH)	Göteborg (Sweden)	Heating energy	1-2% reduction in heating energy
[113]	Simulations (ESP-R)	The Netherlands	Heating energy; Comfort	Optimal thermal mass ranges from 5 kg/m² during Autumn to 90 kg/m² during Summer
[114]	Simulations (TRNSYS 17)	Sweden	Heating energy; Peak demand; Overheating time	1% reduction for older buildings, to 4-5% for contemporary passive houses
[115]	Simulations (TasEDSL)	UK (1990 and 2050)	Heating energy; Comfort	5-8% increase in heating energy demand, higher overheating risks in bedrooms
[116]	In-situ monitoring and analytical	Italy (Catania)	Temperature	Generally beneficial, impact depends on usage and natural ventilation
[25]	Simulations (EnergyPlus) and in-situ monitoring	Italy	Temperature; Costs	Retrofitting high capacity building with thermal insulation worsens thermal comfort

Thermal mass for dwellings in warm climates

In relatively warm climates, the impact of inertia appears to be more pronounced compared to colder regions. On the impact of thermal mass on cooling energy needs, the literature reveals some discrepancies, as some of the studies indicate that the cooling energy demand might rise due to increase thermal inertia in warm climates. Ferrari points out that contrary to popular belief, the impact of thermal mass in the Italian climate is more apparent on winter heating demand than cooling. [108] For the hot desert climate of Las Vegas (Nevada, USA) Zhu et al. concluded that increasing thermal mass in walls reduces the heating energy demand, but increases the cooling load. [46] This is attributed to the fact that high ambient temperature and solar radiation cause the walls to store more energy during daytime, than can be dissipated during the night, thus increasing the net cooling demand. For a 4 zone TRNSYS model of a building located in Cyprus, Kalogirou et al found the optimum value of wall thickness to be equal to 0.25 m. [117] A reduction in the heating load requirement of the zone by about 47% is reported when using a heavy mass wall, whereas at the same time an increase of 4.5% of the zone-cooling load is exhibited. Although the annual cooling consumption is higher than the heating consumption, this results in an overall reduction of 9% of the total energy consumption.

Kossecka and Kosny investigated six different wall configurations for a simple one zone continuously used residential building located in six different USA climates. [24] From an energy perspective, a setup with all massive layers at the inner side and directly exposed to the interior space is the preferred solution. The total energy demand for the least performing configuration with all insulation inside is 2.3% to 11.3% higher, depending on the climate. For most cases, the impact on cooling load is more pronounced than the impact on the heating load, although for the locations Miami and Phoenix the heating load is more affected.

Thermal mass for dwellings in moderate and cold climates

Scientific literature shows conflicting opinions on the net impact of the level of thermal inertia in residential buildings in the temperate or cold north European climate, where active cooling is generally not needed. Some publications denote a preference for lightweight construction methods in such climate, especially in case of intermittent heating schedules. CIBSE Guide F [119] suggests that less thermally massive buildings have shorter preheat periods, and use less heating energy. Based on simulations with a reduced Matlab simulation model, Karlsson et al. conclude that there are cases in which thermal inertia is a clear disadvantage, for example for intermittently heated buildings. Finney states that overall, a high inertia house will use at least 10% more energy, dependent on the level of insulation. [120] Most authors disagree with these statements and predict energy savings for heavyweight buildings in moderate to cold climates. In 1984, Hauser concluded based on an extensive literature review of real life cases that thermal mass can attribute to energy savings in buildings, but the overall impact is small compared to that of the thermal transmittance (U-value) which is about 10 times larger [118]. A study by Tuohy et al. concludes that the effect of thermal mass varies with insulation standard, climate and occupancy/gains scenario [107]. For most of the cases, high mass buildings outperform the low mass variants with both lower heating and cooling demand. Only for buildings with low heat gains in Northern UK climate region, the low mass buildings have a benefit regarding the heating demand. This holds for both U=0.1 W/m²K and U=0.3 W/m²K variants of thermal insulation. It is commented by Tuohy et al. that the high mass house analysed in the Finney article was built in 1976 and thus not complies to contemporary energy performance standards and that it contains significant cold bridging and a high ventilation rate which can contribute to the poorer performance. [107] Hauser concludes that for a German house, the level of thermal inertia has a negligible influence, with a maximum difference of 1.6% on heating energy demand [121]. Jaunzems et al. investigate the impact of changing the thermal mass of the building enclosure of a residential multi-storey building in Latvia. [111] By increasing the thermal mass of the building by 20%, the cooling load of the building decreases by 1.2%, which makes the authors conclude that the thermal inertia has no significant influence on the cooling load for this kind of building in the Latvian climate. For the case of well insulated buildings in Nordic European countries, Kalema et al. conclude based on an analysis with 6 distinct BEPS software packages that increasing the thermal mass will decrease noticeably the cooling demand (30-50% reduction). [47] Increasing thermal mass showed to have a far less pronounced effect on the heating energy demand, which will reduce by 4% for houses with a window area equal to 12% of the gross floor area. For buildings with larger window surfaces (up to 45% of the floor area), the reduction in heating demand can amount to 15%. When a lightweight single-family house is constructed with a concrete floor, the effect of thermal behaviour becomes closer to that of a heavy weight building. Norén et al. report even higher potential savings of 14 to 18% reduction of heating demand for Swedish houses. [103]. The potential savings presented by Heier et al. are much smaller: ranging from 1% for older buildings constructed in 1940, to 4-5% for contemporary passive houses located in Sweden.[114] The impact on the overheating hours is much more expressed with a 20% reduction when replacing a lightweight structure with a concrete external wall.

Dependence of thermal mass effects on season and ventilation strategy

Kendrick et al. evaluated a typical three bedroom UK house. [115] For the heavy weight cases an increase of heating load of 5-8% was found, which the author contribute to the highly intermittent heating schedule imposed. The overheating in the living room is reported to be slightly reduced in the building with higher thermal inertia. The differences are small as the ventilation system is able to expel heat effectively in the lighter constructions with a faster thermal response. For the same reason, the bedrooms in the lightweight buildings actually have lower overheating risks during occupancy, as the heavyweight variants tend to store the daytime heat gains whereas these can quickly be removed by ventilation during the evening in the lightweight rooms. For the 2050 projected warmer weather scenarios, it was concluded that there is little difference between lightweight and heavyweight building constructions, provided that natural ventilation and solar shading are put in place.

Bellamy and Mackenzie have monitored two side-by-side test houses in New Zealand over a period of 25 months. [49] The test buildings were nearly identical apart from the level of thermal mass in their walls. It was concluded that heavy walls provide a good means to increase thermal comfort. The impact on the energy demand is less straightforward and strongly dependent on the ventilation rates. The authors conclude that "Simply replacing lightweight walls with heavy walls of equivalent R-value may increase or decrease the heating requirements depending on the house design, climate and occupant behaviour".

Stazi et al. investigated the renovation of high thermal mass Italian houses a by means of monitoring and simulation. [25] The application of thermal insulation proved to be beneficial with regards to heating demand but detrimental for comfort in summer as the overheating hours increased with over 50% in case of external insulation and almost tripled in case of internal insulation. The introduction of a massive clay panel brings the latter down to an increase of around twice the initial overheating hours. The authors suggest a ventilated insulation system to overcome these problems and combine the contrasting demands during winter and summer time. Hoes et al. also conclude that the optimal amount of thermal mass is sensitive to the seasons and occupancy patterns. [113] For a Dutch residential case study building with intermittent, optimal thermal mass ranges from 5 kg/m² during Autumn to 90 kg/m² during Summer. The authors introduce the concept of hybrid adaptable thermal storage (HATS), which adds non-permanent thermal storage to a lightweight building. An energy reduction of 26% and reduction of weighted over- and underheating hours by 85% is reported based on simulation results.

Design guidance on thermal mass in dwellings

Some authors have attempted to derive design guidelines on the use of thermal mass in residential building design. Slee and Hyde performed an evaluation of 'rules of thumb' for Australian climatic conditions, and proposed a conceptual model of cascading rules of thumb. [122] In a follow-up work by Slee et al. it was suggested that there is likely an upper limit of mass, where beyond that level (in case 80 $kJK^{-1}m^3$ for the Sydney building) additional thermal mass will have little to no impact on the diurnal temperature range of that space. [123] Balaras points out that thermal mass must be properly distributed around the building depending on the orientation of a given surface and the desirable time lag. [32] North and east surface orientations are claimed to have little need for time lag, whereas for a south and west side, an 8 h time lag is sufficient to delay heat transfer from midday until the evening hours. Because of the roof being exposed to solar radiation during most of the day, a construction with a long phase lag is suggested. Nonetheless, most author only considered wall assemblies in their studies. Ulgen suggest using multi-layered and insulated wall formations for buildings which are used all day long, such as houses and offices. [30] For buildings which are used for specific time intervals, single-layers formations are favoured by this author. Gregory et al. conclude through AccuRate simulations that thermal mass needs to be increased proportionally as window area increases. Reverse brick veneer proved to have the least fluctuation in indoor temperature. Their analysis is restricted to one specific day and one climatic data file for Australia. [15] The simulations undertaken by Shaviv et al. indicate that when the total quantity of thermal capacity increases, the impact of additional thermal capacity becomes less apparent. [6]

Guglielmini used a mathematical model to conclude that besides the envelope thermal mass, the thermal capacity of the internal components such as partition walls and floors should not be neglected since they can contribute to a considerable reduction of the inside air temperature fluctuation. [39] The amount of this impact depends on the thermo-physical properties of these structures, the surface area and the presence of insulation layers. The time lag between outdoor and indoor temperature fluctuations is observed to be scarcely affected by the internal thermal mass. Taylor and Miner propose a metric to assess to what extent common interior finishes such as flooring and countertops can add to the thermal mass of a building. [124] In this metric the location-specific variables climate, electricity price, material price and thermal insulation are integrated, but the eventual energy performance gains of the thermal mass itself have not been evaluated.

It can be concluded that most authors claim that residential buildings can benefit from increased thermal inertia, although the amount of savings to be expected shows huge variation amongst the respective authors. The discordance can be attributed to numerous factors, including the authors' assumptions on thermal transmittance of the building envelope, local climatic conditions, and analysis method. This will be further elaborated in section 4 'Discussion'.

3.3 Evidence on thermal inertia effects in office buildings

Besides residential applications, office buildings received special interest of several authors on the subject of thermal inertia. Because of the relatively high internal heat gains of occupants and equipment such as computers and artificial lighting, they are more prone to overheating risks, especially on days where the internal gains coincide with significant external gains from solar radiation and transmission trough the envelope. [125,126,110] The intermittent occupancy of most offices allows for optimization of the heating and cooling demand, making use of the thermal inertia of the building components. [127]

In a 1981 paper Guglielmini et al. conclude that thermal inertia is less suited for energy saving purposes in commercial buildings, as the heat gained by the internal and envelope mass will also be released during unoccupied hours. [39] For many contemporary commercial buildings however, the cooling needs are now the most crucial factor, even in moderate or cold climates. Exactly this behaviour of storing heat and releasing it later helps to cut down on cooling demand and especially the peak consumption of the cooling plant. The thermal capacity provided in floors and walls can absorb excess heat during daytime, to remove this during night hours by ventilation when the buildings are not in use. [16] Chlela et al. have developed a methodology using meta-models to restrict computing time in parametric analysis of low energy buildings. [128] The Design of Experiments (DOE) method used, reduces the required number of experiments or simulations by developing mathematical models describing the behaviour of the studied system with respect to some influencing factors. One of the influencing factors studied by Chlela et al. is the thermal inertia of a building. The case study building examined is a three-story office building located in France for which both the cities of Nancy (cold climate), Agen (moderate climate) and Nice (hot climate) have been considered. The authors conclude that the thermal inertia of the building induces non-linear variation in the meta-models of the annual heating demand, which would require second order meta-models. This is depicted in Fig. 3, where the annual heating demand for a 'medium mass' building is considerably lower compared to a lightweight building, but rises again if the thermal mass is further increased.

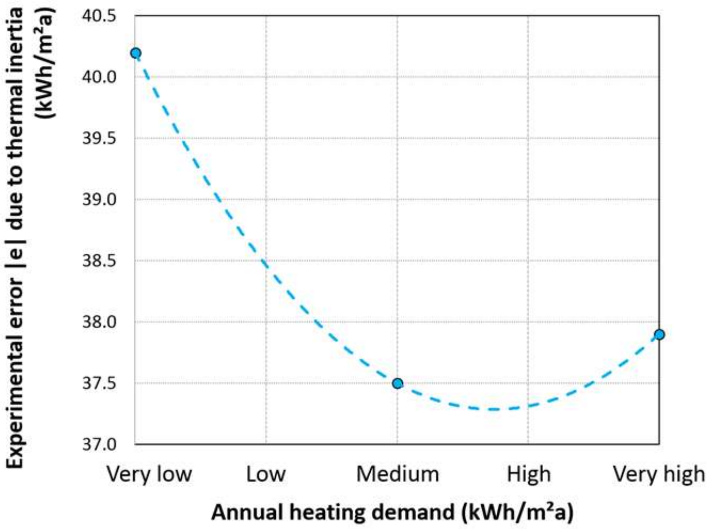

Fig. 3 Non-linear variation of the factor Inertia in meta-models describing the energy demand of a 3 story office building located in Agen, France. Graph created after Chlela et al. [128]

Ståhl reported heating and cooling demand reductions due to increase thermal mass of 4% in Swedish office buildings. [112] Although these are higher compared to the savings of 1-2% for residential houses reported in the same work, the author claims the differences are so small they fall within the error margins of the calculation.

Taylor et al. performed a case study analysis on a two-story rammed earth office located in Wodonga – Australia. [17] The building was constructed in 1999 and received a special jury award from the Royal Australian Institute of Architects for environmentally sound design. Green building features of the building include rammed earth external and internal walls, radiant heating and cooling supported by flat plate solar collectors and natural night ventilation. Measurements and questionnaires found the building was too hot in summer and too cold in winter. Despite the green features the building has shown to exceed the energy targets specified by the Australian building codes at the time of construction.

Yang and Li conclude that the time constant τ of a building is a critical parameter for describing the effect of the thermal mass on building operation. [54] The time constant τ expresses the phase shift of the thermal mass of the building as a whole, and is defined as $\tau = Mc_m/\rho c_p q_v$. By including a reference ventilation rate q_v, which the authors chose to be equal to the night ventilation flow, the concept of time constant τ of a building not only incorporates thermo-physical properties of the building envelope, but also includes an operational characteristic. In their analysis of a simple office building model, they conclude that the peak cooling load is delayed and energy savings are achieved when the time constant τ increases. For values of τ exceeding 1000 however, there is a minor increase of the total cooling load. This is attributed to the fact that the rate of ventilation in their building model is lower at night. Time constants τ approaching the value of 6h, may lead to keeping the thermal mass of the building at a high temperature during the night, hence slightly increasing the cooling load the next business day.

Aste et al. performed a parametric simulation on an air-tight and well insulated case study office building, for which 3 different Italian climatic regions are considered. [110] They stress that the potential advantages of thermal inertia depend on the specific intermittent operating conditions, and further explore this by introducing adaptive shadings and night free cooling in the simulation model. The authors conclude that the performance advantage for heavier buildings is hardly noticeable in some of the cases, and becomes only relevant (15-30% reduction in cooling demand depending on the location) in optimized cases in which increased night ventilation is present. This is attributed to the fact that in air-tight and well insulated buildings, the air-change rate is limited and therefore not sufficient to enable a passive cooling process by itself.

Schools exhibit an occupancy profile that is somewhat similar to that of office buildings. Orosa and Olivaire undertook a measurement campaign in two Spanish schools, and concluded good correspondence with the dynamic thermal simulations. [129] Despite the higher thermal mass, the newly constructed school building displayed a higher overheating risk, which underpins that differences in internal heat gains and solar gains can have a greater impact on the thermal behaviour than differences in thermal mass. Based on monitoring data and calibrated simulation models, Di Perna et al. conclude that the use of a massive wall in a school building in Loreto, Italy, can reduce the amount of overheating hours by 6% compared to a lighter structure. [130] The authors introduce threshold values for the internal areal heat capacity, which are proposed to be adopted in regulations based on steady semi-steady state building energy assessment methods. The approach suggested by Di Perna et al. could also be applicable to other building types such as office buildings.

A high amount of thermal mass of in a building dampens the temperature fluctuations, which will affect the indoor thermal comfort of occupants. Comfort is not a state condition, but rather a state of mind which is influenced by physical, physiological, psychological, and other factors. [131,132] An increase in thermal comfort can have an important impact on the productivity of office workers. [133–135] Buildings owners and occupants who adopt climate control strategies that improve the comfort, e.g. by harnessing building thermal inertia, can retrieve significant financial advantage from this, often surpassing the direct financial gains related to the lower operational energy costs.

Based on the literature reviewed it can be concluded that office buildings with significant amounts of exposed thermal mass will generally exhibit a lower energy consumption and a more favourable indoor climate compared to lightweight alternatives, although the exact figures vary greatly amongst the authors. A proper control of heat gains and ventilation rates is essential to harness the potential beneficial impacts of the thermal mass. Some results indicate that too high amounts of thermal mass might negatively affect the performance.

3.4 Utilising thermal inertia effects to enhance building operation

In the previous paragraphs, it has been demonstrated that the thermal inertia of a building can have significant impact on the thermodynamic behaviour of a building. The amount of thermal mass can affect total cooling and heating energy needs, but also the peak loads on the HVAC systems, and the indoor thermal comfort during free floating operation. Building designers, HVAC engineers and building occupants can exploit this behaviour in order to create buildings which are more comfortable or more economic to operate. This section of the paper explores four specific applications of building thermal inertia.

3.4.1 Optimizing thermal mass to reduce system peak loads

A common building control strategy is *'Night setback/ Night setup'* in which the thermostat set point is set to a lower temperature for heating or a higher temperature for cooling during night. [136,137] During night-time the building is not occupied, and the thermostat control set points can be less strict. In some cases the equipment is completely switched off, allowing the building to operate in a 'free float' modus. [138] Thermal mass in a building could potentially impose the need for higher maximum HVAC system capacities. During intermittent use, the system does not only have to heat or cool the indoor air, but a significant additional amount of energy is also required to bring the building thermal mass to the desired temperature. An imaginary massless building would require smaller HVAC systems an requires no time for precooling or preheating, which could result in lower energy consumption. [139]

In reality however, many cases have proven that a proper use of a building's thermal storage can significantly reduce operational costs for heating and cooling. Thanks to the slower reaction of a thermal inert building, peak loads can be shifted with proper control strategies. This allows to undersize HVAC installations and thus reduce investment costs, and can help to shift heating or cooling loads to off-peak hours. In case of time-of-use (TOU) utility rates, energy costs can be lower during off-peak hours, e.g. during night and weekend. The total energy costs might thus be lower, even though the total zone loads may increase. If the building thermostat operates with a dead band between cooling and heating regime, harnessing the building thermal mass can even reduce the total heating or cooling load demand because the building structural mass represents a passive building thermal storage inventory that can serve as a heat sink. [136] This property is exploited in buildings using intensive night ventilation strategies to reduce the cooling demand. [6,125] The colder night air will pre-cool the buildings, thus reducing or fully eliminating the cooling demand during the next business day. Especially for summer overheating, the thermal mass of a building can delay the temperature built up during days with high outdoor air temperature and with significant solar irradiation. Depending on local climatic conditions, it is often feasible to construct buildings without an active cooling system, for which the thermal mass of the building acts as a passive-thermoregulation. [140]

Henze et al. used dynamic building energy simulation tools to systematically analyse the impact of various pre-cooling strategies for a three story office building located in Phoenix, Arizona. [136] Parameters in this study are the utility rate structure, the occupancy pattern, internal gains generated in the building, temperature set-point profile and the outdoor climatic conditions characterized by the diurnal temperature and relative humidity swings. Increasing the building mass showed to reduce cooling loads. By doubling the mass level, e.g., the noontime cooling reported by the authors drops from 460 kW to 390 kW. The cost savings relative to the reference case were found to be maximized for intermediate and not the highest mass levels of the building construction. This is attributed to the fact that while increasing the building mass, cooling requirements decrease more sharply than the opportunity for load shifting grows because building precooling only makes use of part of the thermal mass in the diurnal precooling process, while the total building mass reduces the envelope cooling loads. Miura analyses a combination of measurements and building performance analysis data to investigate the effect of a thermal storage system in an office building located in Sapporo, Japan. [45] The total thermal load on the air handling units is 3% to 10% higher than the base case without a thermal storage in building mass (TSBM) operation. The maximum hourly thermal load imposed on the HVAC system was reduced by 40% when TSBM operation was adopted, which allows to significantly reduce the capacity of air handling units.

It can be concluded that with a proper control strategy, thermal inertia in a building can indeed be effective to reduce the heating or cooling peak loads. This can come at the expense of higher annual total heating or cooling demand. Savings in capital expenditure for smaller HVAC installations, and savings in operational costs through the use of off-peak energy or even 'free' cooling through intensive night ventilation can compensate for this.

3.4.2 Thermally activated building systems

The effects discussed before can be further exploited by using thermally activated building systems (TABS). In this concept, the building structure and its thermal mass are considered as an intrinsic part of the building's HVAC system. Mainly because of low investment costs and favourable comfort, the use of thermally activated building systems for the heating and cooling of buildings has spread widely throughout Central and Northern Europe in recent years. [141] This type of HVAC systems is also referenced as 'slab cooling and heating system', 'concrete core conditioning', 'thermally active mass' and 'building integrated thermal energy storage'. [29] A common example of TABS is a system in which the pipes of the cooling and/or heating system are embedded in the load bearing concrete floor. The floors or the building will thus serve as radiant heat or cold emitters. The large heat or cold emitting surfaces in TABS allow to heat at low temperatures and cool at relatively high temperatures, which increases the efficiency of many heat and cold generating devices. A study by Saelens et al. reported such a system to be able to deliver good thermal comfort, but requiring a cooling demand which exceeds the base case scenario without TABS by 8%. [142] By using the TABS, the peak loads on the cooling plant can be reduced thus reducing the size and costs of the installation. A case study in the cold Hokkaido region in Japan reported a reduction of the maximum hourly thermal load of 40% when TABS was adopted in an office building. [45] Additional profit can be gained from operating the cooling plant during off peak hours and by making advantage of the colder night-time air for direct ventilation.

Another specific application of TABS are Trombe walls, which are named after the French engineer Felix Trombe. He popularized the concept first described by Edward Morse in 1881. [143] The integration of Trombe walls as an architectural element gained public interest in the 1960s. [144] Trombe walls are massive walls, mostly made of concrete or heavy bricks, which are separated from the outdoors by an external glass layer and an air space in between them. The aim of Trombe walls is to absorb solar energy and re-radiate it to the room as shorter wavelength infrared radiation. By properly selecting the wall's thickness and composition, the Trombe wall can capture solar thermal gains during daytime, and transfer these to the indoor thermal environment during the night. Vents can be added at the bottom and top of the glazing to increase the solar chimney effect in the air space. Some of the Trombe walls also feature vents in the massive wall itself, which allow to circulate indoor air at the solar exposed side of the wall and thus make the heat dissipation of the Trombe wall more controllable. [145]

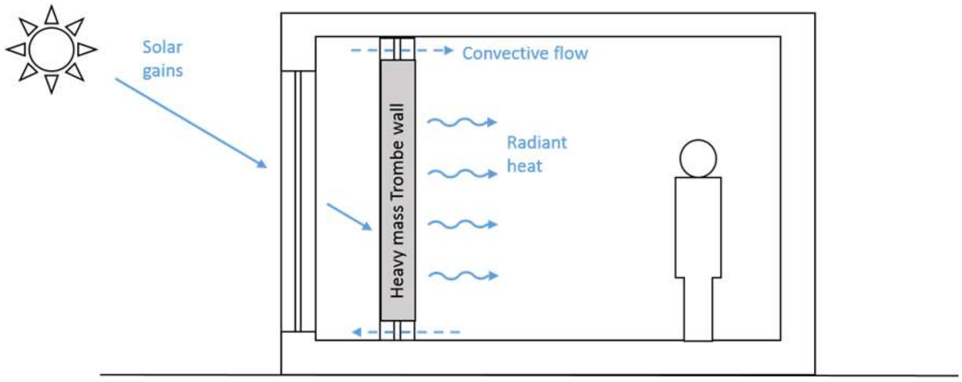

Fig. 4- Conventional Trombe wall

Childs et al. rightfully claim that thermal mass is effective when a building experiences alternate periods of net energy gain and loss. [23] The maximum benefit occurs when the alternating losses and gains average near zero. When this occurs, thermal mass can potentially eliminate heating and cooling loads. The Trombe wall is a specific technique which can be part of such a climatic responsive design, however it can hardly ever totally eliminate the need for dedicated heating and/or cooling systems.

3.4.3 Load balancing in smart grids and demand side management

Many of the renewable energy sources do not provide a stable output of electrical power, this is notably the case with photo-voltaic (PV) solar power or energy from wind. By using the ability to time-shift the energy demand of an energy consumer, the demand can be aligned to the available excess energy of renewable energy sources. This principle is referred to as demand side management (DSM). The electricity networks need to integrate two-way communication to enable integration of real-time control. These networks with additional intelligence are often referred to as Smart Grids. The energy demand of buildings is to some extend flexible in time and can also be part of DSM control. This allows the building to maximize self-consumption of its own solar energy generation and potentially also cost-efficient incorporation of excess electricity from centralized wind or PV farms, thus helping to maintain grid stability. [147]

A common way to implement DSM in building operations is using optimized control algorithms for domestic hot water boilers. [148,149] Water is one of the best sensible heat storage liquids for temperatures lower than 100 °C because of its availability, its low cost, and relatively high specific heat. [150,151] The building structure itself can also serve as an actively controlled thermal storage system. A dynamic control strategy can be implemented in which the building is preheated or precooled when the time-of-use electricity price is low. The need to keep within acceptable indoor thermal comfort limits will restrict the amount of precooling or preheating that is attainable. Applying such a dynamic control algorithm, cost savings ranging from 0 to 14% are documented by Greensfelder et al. for day-ahead real time electricity rate structures applied to 3 office buildings located in the USA. [152] Low internal gains and high thermal mass proved to result in a more flexible precooling strategy. Henze et al. investigated the merits of a combined control of the passive storage of thermal loads by precooling the building structure and the active thermal energy storage systems such as ice storage. [153] Based on total utility cost, savings of about 16% were reported for either passive- or active-only thermal storage compared to the base case without storage. An optimal control for both technologies resulted in savings of 26%. Reynders et al. investigated the case of dwellings located in Belgium which are heated by an electrical heat pump. Not surprisingly, the DSM potential is found to be higher for heavy mass buildings compared to the light-weight alternatives, and floor heating systems outperform radiators.

Wolisz et al. investigated the effect of furniture and floor covering under dynamic temperature control conditions. [147] According to their findings, an empty massive room can get 1.2 K warmer after 4 hours of increased set temperature compared to the same modelled room with laminate flooring and furniture inside. This effect is especially important when considering low temperature heating systems such as electrical heat pumps using radiative heating. They point out that when considering the demand-shifting potential of buildings, the scope of operations which matches the comfort range of residents can be further reduced when accounting for the effect of furniture and floor coverings. As one would expect, their results confirm that for lightweight buildings the effect of furnishing and floor coverings is more expressed, since it contributes a larger share of the total thermal mass.

It can be concluded that buildings with high thermal inertia can be used as part of DSM control strategies, provided that the operation remains within narrow thermal comfort limits.

3.4.4 Phase change materials

Phase change materials (PCM's) are materials which use latent heat storage: the thermal energy transfer occurs when the aggregation phase (also referred to as '*state*') of the material changes from solid to liquid, or liquid to solid. Just like 'traditional' heavy mass constructions, these materials have the ability to raise the building thermal inertia and stabilize the indoor climate for the occupants without requiring additional energy for heating or cooling. The main property of phase change materials is the storage of heat energy in a latent form, leading to greater heat storage capacity per unit volume than that of conventional building materials. [154] They can be utilized in passive storage systems such as use in walls or active storage systems such as floor heating setups or part of the ventilation system. [155] Besides sensible storage and latent heat storage using PCM's, energy can also be saved by using thermo-chemical storage. This is especially useful in cases where low volume, high density storage is requested. [150]

The review paper of Zhou et al. provides an extensive overview of PCM applications in the building sector. [156] Technical properties which will affect the choice for a PCM for a particular application are the phase change temperature range, the latent heat of fusion and the depending on the application the long-term chemical stability and the absence of phase segregation. [154,157,158] Commercially available PCMs used for passive storage in a building often have melting temperatures between 20 and 32 °C. [159,160] The melting enthalpy and melting temperature for the PCMs have to be properly selected to cater for the specific use in the building and the climatic conditions under which the building will be operating. [154] A common use of PCM in building construction is the integration into wallboard material. Installation of wallboard with 400kJ/m² latent capacity would attribute a distributed thermal storage which is roughly equivalent to that in a building with masonry on all internal surfaces. [161] Zeng et al. investigated the inverse problem, and propose an analytical approach to calculate the ideal specific heat of a building envelope. [162] From an energy saving perspective, it is concluded that the ideal building envelope material has the thermal mass characteristics of phase change material. The approach is tested for 7 cities in diverse climatic regions in China. The optimal thermo-physical properties of the building envelope are showed to be dependent on the applicable comfort range and the climatic zone where the building is located.

Based on evidence in literature PCM's can be an effective way to increase the thermal inertia of a building, with the additional benefit of being able to select material properties such as melting temperature which can cater to specific needs. The market uptake of PCM's is relatively low, which could be attributed to the associated costs, limited knowledge on PCM's amongst building most designers and engineers, and the low availability of products on the market.

4 DISCUSSION

The results of studies on building thermal inertia reviewed in this paper generally tend to conclude that additional thermal inertia in a building can increase its comfort and reduce the energy demand, although some unfavourable cases have been reported as well. The exact contribution of thermal inertia is hard to ascertain, e.g. regarding impact on energy demand extreme figures ranging from +10 to -80% have been reported. This apparent discordance can be attributed to the following causes:

1. The effect of thermal inertia inherently depends on the time varying nature of the heat flows. The daily swing of outdoor air temperature and solar radiation is one of the most defining factors. From this fact, it is clear that the climatic conditions will have an important impact on the result of any study investigating the effect of thermal inertia in a building. Some authors tried to overcome this by studying buildings in a range of different climatic conditions, or resorting to synthetically generated climate data, such as sinusoidal daily temperature profiles. The latter approach has the benefit of being more generic, but does not properly reflect the dynamics of real world weather conditions and often negates the important contribution of solar radiation entering the building through the transparent parts.
2. The complexity of the phenomenon and the lack of proper metrics and standards to describe the effect of thermal inertia in a uniform way across all studies causes deviations in the results. Section 2.3 already pointed out that many parameters are used in practice to describe thermal inertia, such as total thermal mass, thermal diffusivity and phase lag. Some authors even fail to quantify the thermal mass properties of the buildings under study – e.g. by just denoting them as 'heavy' and 'light', which makes it hard to compare their findings.
3. The authors use a large variety in different research methodologies. Some of them present metered data from actual buildings, whereas other authors rely on building performance simulations. A few authors even use a strictly analytical approach. Although the impact on the research outcomes can be significant, all of these research methods have their specific merits, so no single approach can be labelled as superior.
4. In case the study relies on computer simulation, a multitude of methodological choices can attribute to deviations amongst the study outcomes. At present many capable building performance simulation tools are available to choose from [69,163,164]. Although most commonly used building performance simulation tools have been validated, e.g. according to the BEStest certification procedures, the calculation procedures used within these tools may differ. [165] Some software tools even have the capability for users to opt between several calculation routines; e.g. EnergPlus 8.5 allows the user to choose amongst 5 distinct heat balance algorithms, including 'conduction transfer functions' and the 'combined heat and moisture finite element' algorithms. Together with other factors - such as the calculation time steps, the methodology used for air transport modelling, etc. - these settings could have an impact of the simulation outcomes and thus the reported savings attributed to thermal inertia. Nevertheless, many authors fail to provide a full description of the settings and parameters used as part of their research, making it hard to compare the results across studies.
5. Some authors limit their analysis to wall or roof assemblies, whereas others consider a building as a whole – including variable thermostat set points, heat gains through windows, real life occupancy patterns, etc. The latter approach will enable a more in-depth analysis of the contribution of the thermal inertia to occupant comfort and energy use in realistic conditions. Such a more elaborate analysis introduces a significant amount of extra parameters including building dimensions, window size and orientation and occupant behaviour profiles. While being more realistic, the downside of such a detailed whole building simulation is that the analysis will have to be based on a case study approach, thus limiting the overall applicability of the research outcomes.
6. The energy use and indoor thermal comfort in a building are influenced by a multitude of physical phenomena, building characteristics and occupant behaviour. As a consequence, the thermodynamics of a small scale residential building differ greatly from a contemporary high rise office building due to the large distinctions in parameters such as building properties and occupancy patterns. Results on the

analysis of building thermal inertia which were derived for one specific building type cannot be simply transferred to other building typologies. And even for a given building type, many parameters such as the occupancy patterns, glazed surface, thermal insulation, HVAC systems, etc. all have a significant impact, again making it hard to compare results across multiple studies.

7. The KPIs targeted by the different authors can vary greatly: reducing total cooling demand, reducing total heating demand, reducing HVAC system peak loads, lowering operating cost considering variable energy pricing, optimizing indoor thermal comfort, etc. That way, the reported 'optimal' thermal mass of a building can have various meanings depending on the goals of the optimization process set by the researchers. Although the performance indicator 'energy use' is used by many authors, the exact definition of it showed to vary greatly amongst the studies reviewed. In some studies the authors analyse the cooling or heating needs, whereas other studies report the energy uptake from the HVAC systems, thus including production and distributing efficiencies from the system components. In some studies the primary energy consumption is reported, which also encompasses the conversion rates of primary energy sources. Especially in the case of electrical energy, the conversion factors for primary energy display large regional variations, depending on the local energy mix.
   Besides energy demand, thermal comfort is another KPI assessed by many authors, eventhough the literature review shows that for the assessment of comfort multiple distinct metrics are used, such as percentage of occupied time the indoor air temperature surpasses a set point chosen by the author, PMV/PPT scores according to the Fanger equations, adaptive comfort indicators, etc., which further attributes to the range in research outcomes occupied time the indoor air temperature surpasses a set point chosen by the author, PMV/PPT scores according to the Fanger equations, adaptive comfort indicators, etc., which further attributes to the range in research outcomes with regard to the effects of thermal inertia.

5 Conclusion and outlook

Exploiting the benefits of transient thermal behaviour is often advocated as a vital component of passive solar building design strategies. Buildings which contain large amounts of thermal capacity within the thermal envelope can store and progressively release large quantities of heat, thereby time-shifting and attenuating temperature excitations. In the past analytical methods have been used to study this thermal inertia effect. With the advent of capable dynamic whole building simulation tools, these methods have nowadays become obsolete. The use of these dynamic simulation tools is widespread in academic research, but many building design practitioners nevertheless still use steady state analyses. Solely relying on parameters which describe steady state thermal resistance (R-value) or thermal transmittance (U-value) however fails to encompass the dynamic behaviour resulting from time-varying outdoor conditions and building usage.

A large body of literature on the effects of thermal inertia is available. The analysis on building component level provides ample evidence that the order of layers in a structure is an important factor in the dynamic heat transfer. Most studies on component level have focused on wall assemblies, even though roofs are often exposed to more pronounced temperature fluctuations. For assessing the actual impact of thermal inertia, studies on the scale of whole buildings are more valuable than a simple component analysis. On the scale of a building the effects of heat storage and release can be studied in conjunction with the governing heat flows resulting from solar heat gains, occupants and air flows. Only a few comparative monitoring campaigns have been reported in literature, since these studies are expensive and provoke difficulties with discriminating the effects of thermal inertia from other variables. Most researchers have instead relied on building performance simulations, for which a huge range of tools and modelling approaches can be witnessed.

As a consequence of the wide range in research methods, parameters such as climates and KPI s studied, the literature displays a scattered view on the effects of thermal inertia. Nevertheless as a general tendency it can be concluded that most authors report that thermal inertia can have a positive impact on the indoor thermal comfort. The results on energy demand show more variation. Most authors predict a slight reduction of heating energy use in massive buildings, although conversely small increases in energy demand are also reported for intermittently heated buildings in cool climates. For some cases- especially non-residential buildings in a warm climate- an increase in cooling energy is found, but evidence suggests that proper (night)ventilation strategies can overcome this. Overall the reported impact of thermal inertia on energy demand is relatively small. For residential buildings the energy savings reported are often in the order of magnitude of a few percent, which is far less pronounced than the impact of other energy saving measures such as increasing thermal insulation of the building envelope. Controlling the heat gains and ventilation is paramount to the effect of thermal inertia, especially for non-residential buildings.

Some design guidelines on optimal thermal inertia have been reported. In order for thermal mass to reduce energy usage of a building, the building must undergo alternating periods of net energy gain and loss. Therefore it is evidently that the optimal design will be dependent on the climate the building is conceived for, so these guidelines should be used with caution.

The effect of thermal inertia can also be actively exploited as part of the building design and its HVAC operations. With a proper control strategy, additional thermal inertia can reduce the heating or cooling peak loads. This allows to have smaller HVAC installations, but might introduce a greater overall heating or cooling demand. By delaying this to cheaper off-peak energy consumption or 'free' cooling using night ventilation, the energy costs can nevertheless be reduced. Especially in office buildings, characterised by a high internal heat load from people and electronic equipment, heat or cold storage have proven to be beneficial. This effect can be further pursued by integrating active HVAC systems in the thermal mass components, the so-called thermally activated building systems (TABS). A relatively recent addition to the research field is the active control of a building's thermal mass as part of load balancing efforts in a smart grid context. More thermal inertia allows to exploit this to a further extent, but the narrow thermal comfort limits remain an important boundary condition to consider. In case thermal inertia cannot be attained by heavy mass materials, latent energy storage using PCMs can result in similar behaviour.

Based on the findings in the literature review, some suggestions for future research on the topic of building thermal inertia are suggested.

Since many parameters influence the exact contribution of thermal inertia, the recommended solution to retrieve detailed information for a given building design is using BEPS software to make a case specific dynamic simulation model of a building - including its geometrical properties, usage patterns and local climatic data. Although the use of dynamic building simulation software to assist the design of a building is encouraged, generic guidelines can prove to be useful in the early design stages, or for small scale projects where the use of BEPS software is often not considered to be financially feasible. Some attempts to provide such design guidance have been documented in literature, but these can be further elaborated with a more systematic approach to include multiple variations of building thermal mass, building typologies, occupancy patterns, climatic zones, etc.

An apparent omission in many papers on the issue of thermal mass in buildings is that they focus on thermal mass present in the building envelope, thereby neglecting the contribution of the building inner partitions and furnishing to the total thermal inertia of the buildings. This is equally the case for residential buildings as office buildings. It remains to be further analysed to what extent thermal capacity inside the building envelope can indeed influence the thermal behaviour. There is some evidence suggesting that in some climates a minimum level of thermal capacity is needed for a building to have an acceptable indoor climate. Additional investigations could explore whether adding thermal mass in the interior of a building can compensate for the lack of thermal capacity in a building envelope.

Many research findings suggest that the effect of thermal inertia is to a large extend dependent on the building operation, which includes the ventilation and solar shading strategies. Further research is needed to assess how this can be optimized, and whether a lower level of thermal inertia in a building can be effectively compensated by proper building operation strategies and provisions such as external shading devices.

For buildings with highly intermittent use, the thermal inertia could potentially be detrimental, as the slow reaction of the building thermal mass could cause discomfort or additional energy expenditure, but little quantitative data to support this assumption is reported in literature. Some researchers have suggested concepts of adaptable thermal mass, ventilated thermal insulation or room specific thermal mass designs. These promising approaches can be further explored, as they might be able to bridge the sometimes conflicting needs in managing the thermal environment in a room or building.

Finally, it should be noted that this review paper on building thermal inertia has focused on the operational energy use of buildings, thereby neglecting the energy required for the production of the building materials, the construction phase and end-of-life demolishment and waste removal. Studies suggest that constructions in heavy weight materials such as concrete have a higher energetic impact over their full life-cycle than comparable structures in wood, which is often deployed as a structural material in lightweight buildings. [166,167] Given the observation that the energy savings contributed to the building thermal inertia are generally rather modest, it is worthwhile to further explore the life-cycle energetic performance of lightweight and heavyweight buildings, taking into account the combined effects of embodied energy and operational energy expenditures for heating and cooling.

ANNEX: PROPERTIES AND PARAMETERS TO QUANTIFY THERMAL INERTIA

In literature many properties and parameters are being used to describe thermal inertia of a building or building component, and the impact thereof. In the following section a limited number of these parameters is listed and briefly discussed.

5.1 Specific heat capacity (c) and volumetric heat capacity (C)

Specific heat capacity is a material property which depicts the energy required to raise the temperature of the material by one degree per unit of weight. A related parameter, the volumetric heat capacity C equals to the specific heat capacity c times the density ρ of a material.

$$C = c.\rho \ [J/m^3K]$$

Conversely, some authors use the symbol C to describe the total thermal capacitance of a building. The specific heats of all of the building elements are summed into one lumped parameter. Antonopolos and Koronaki argue that this approximation is too rough, because the ability of structural elements to store heat is different depending on whether these are distributed in the building or considered to be concentrated in a unified volume. [168] The authors therefore introduce the 'effective thermal capacitance' C_{eff}, and present a calculation procedure to derive this parameter based on measurement data.

5.2 Thermal mass

The thermal mass of a construction is the summed mass of all construction elements of a building, and is sometimes adopted as a simplified indicator of the thermal inertia. The specific heat of most of the building construction materials is within a narrow band of 0.8–1.8 kJ/kg K; therefore the thermal capacity of a building is indeed to a large extend determined by the mass of the construction. [136] . Thermal mass divided by unit area or by building volume would however be a more appropriate indicator, allowing to compare different building designs. As discussed in paragraph 2.3, thermal mass on its own is not sufficient to describe the dynamic thermal effects, since this parameter does not incorporate the rate of energy exchanges, the importance of the order of layers in a multi-layered construction, and thermal inertia effects attributed to latent heat storage in building materials.

5.3 Decrement factor

The decrement factor *f* is a dimensionless factor which expresses the change in amplitude of a sinusoidal heat wave propagating through a material or building component. [41,169]

It is defined as

$$decrement\ factor\ f = \frac{A_i}{A_e} = \frac{T_{i,max} - T_a}{T_{e,max} - T_a}$$

In which A_e is the amplitude of the temperature excitation, and A_i is the amplitude of the response as depicted in Fig. 2 (a). Some authors reference this parameter as attenuation factor *f* [30], amplitude ratio [24], amplitude reduction factor ζ [39] or decrement factor T_D. [15]

5.4 Thermal diffusivity

Thermal diffusivity a is a material-specific property which characterizes the speed at which a thermal excitation moves through a material in case of unsteady heat conduction. A high thermal diffusivity corresponds to a fast propagation of the temperature excitation. The thermal diffusivity is related to the thermal conductivity, specific heat capacity and density. [23]

Thermal diffusivity is defined as: $a = \lambda / \rho c$ [m^2 /s]

The thermal diffusivity of a material can either be calculated from known technical properties, or directly measured, e.g. by using the non-destructive flash method on a small specimen. [170]

5.5 Thermal phase lag

The thermal phase lag ϕ determines how long it takes for heat to go through a given thickness of a material. [30] The thermal phase lag of a wall is graphically depicted in Fig. 2 (b). For a sinusoidal wave it is equal to the thickness squared divided by the thermal diffusivity.

$$\phi = d^2 / \alpha \text{ [s]}$$

For a homogeneous masonry wall of 5 cm, the thermal phase lag is about 1 hour. [171] Some authors refer to this parameter as the admittance time lead, or the thermal time constant of a component. [172] This should not be confused with the time constant of a building τ, which encompasses both the total mass and the effects of the convective heat transfer. [54]

5.6 Thermal effusivity

The thermal effusivity *b* is a measure for the ability of an object to exchange thermal energy with its surroundings. A high value for the thermal effusivity corresponds to a material that can easily absorb and release heat at the surface. Most metals have a high thermal effusivity: despite their high thermal mass, they are not well suited to increase the thermal inertia of a building. They can absorb a lot of heat, but their high thermal effusivity also makes them prone to dissipate the heat at a fast pace to their surroundings.

$$b = (\lambda.C)^{1/2} \text{ [W m}^{-2}\text{ K}^{-1}\text{ s}^{-1/2}\text{]}$$

Some authors use the symbol *'e'* to denote thermal effusivity. [150]

5.7 Thermal admittance

The thermal admittance *Y* of a component is the ratio of the sinusoidal component of heat flux *q* at the surface of a building construction to the corresponding variation in surface temperature *T* . [53,169,173] In contrast to the steady state parameter thermal transmittance *U*, the admittance *Y* is influence by density *ρ* and the specific heat capacity *c* of a construction material. Generally dense materials take up more heat and have higher admittance values than lightweight ones.

5.8 Thermal response factor

The dimensionless thermal response factor f_r is defined as

$$f_r = \frac{\sum(AY) + C_v}{\sum(AU) + C_v}$$

in which *A* is the surface area, *Y* is the thermal admittance and *U* is the thermal transmittance. The ventilation conductance C_v is expressed as

$$C_v = \frac{1}{3}NV$$

in which *N* is the room air change rate expressed in air changes per hour and *V* is the volume of the room. Buildings with a high thermal response factors ($f_r > 4$) are referred to as heavy weight buildings, and those with a low thermal response factor ($f_r < 4$) are referred to as light weight buildings [125,174]

5.9 Other related parameters

Many authors have attempted to introduce additional parameters to quantify thermal inertia effects on buildings, including:

- A dimensionless m-factor, depicting the ratio of instantaneous heat flux over steady state heat flux of a building component [175]
- Eigenvalues and shape of Eigenfunctions resulting from a modal analysis [176]
- Periodic penetration depth δ, which defines the depth at which the amplitude of temperature variations are reduced by a factor e (2.718…) in a homogeneous material of infinite thickness, subjected to sinusoidal temperature variations on its surface [169]
- Equivalent thermal mass area [111]
- Thermal-mass energy-savings potential and critical thermal-mass thickness" which determine thermal mass thickness required for a selected desirable percentage of energy savings.[177]
- Wall dynamic resistance R_d [178]
- The cyclic thickness of a construction component [179]
- Storage coefficient and heat-spreading coefficient [30]
- The effective heat capacity ratio, which expresses the dimensionless ratio of effective capacity participating in a transient thermal process to lumped heat capacity. [95]

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