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Embodied and operational carbon dioxide emissions from housing: A case study on the effects of thermal mass and climate change

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Abstract

A 100-year lifecycle carbon dioxide (CO_2) emissions analysis is reported for a two-bedroom, 65 m^2 floor area, semi-detached house in south-east England. How the balance between the embodied (ECO_2) and operational CO_2 emissions of the building are affected by the inclusion of thermal mass and the impacts of climate change is quantified. Four 'weights' of thermal mass were considered, ranging from lightweight timber frame to very heavyweight concrete construction. For each case, total ECO_2 quantities were calculated and predictions for operational CO_2 emissions obtained from a 100-year dynamic thermal modelling simulation under a medium-high emissions climate change scenario for south-east England. At the start of the lifecycle, the dwellings were passively cooled in summer, but air conditioning was installed when overheating reached a certain threshold. The inclusion of thermal mass delayed the year in the lifecycle when this occurred, due to the better passive control of summertime overheating. Operational heating and cooling energy needs were also found to decrease with increasing thermal mass due to the beneficial effects of fabric energy storage. The calculated initial ECO_2 was higher in the heavier weight cases, by up to 15% (4.93 t) of the lightweight case value, but these difference were offset early in the lifecycle due to the savings in operational CO_2 emissions, with total savings of up to 17% (35.7 t) in lifecycle CO_2 found for the heaviest weight case.

Keywords: Thermal mass; Housing; Climate change; Lifecycle analysis; CO_2 emissions; Overheating; Embodied CO_2

1. Introduction

Climate change over the coming century now seems inevitable, regardless of what can be done to limit anthropogenic emissions of greenhouse gases [1]. A warming climate is now widely accepted as the most likely outcome of climate change with the current set of UK government climate scenarios for the UK indicating increased peak summer temperatures of up to 7 °C by the latter part of this century [1]. One major impact of these changes will be a greater risk of overheating in free-running naturally ventilated buildings. Nearly all dwellings in the UK are free-running in summer and so are particularly vulnerable to the impacts of warmer summers.

A likely adaptation response is that more home owners will seek to install air conditioning in their homes, as has been seen in other parts of the world which experience hot summers and where this option is generally within economic reach, notably the USA, Australia and southern Europe. With domestic energy use currently accounting for around 63% of carbon emissions from the building stock in the UK [2], the air conditioning of homes presents an undesirable scenario with respect to reducing energy dependency and carbon emissions. It is also arguable whether people wish their homes to be 'sealed up' and mechanically cooled in summer, or whether they prefer to have more climatically open building environments.

An alternative approach is to make use of passive adaptation options to maintain indoor comfort levels, which are a mainstay of traditional architecture in warmer regions but have historically been of little relevance to the UK. The main passive design elements are shade, control of daytime ventilation, and use of thermal mass with night ventilation [1]. This paper focuses on the last of these elements: thermal mass.

The effectiveness of thermal mass for reducing summertime overheating has been well established for both domestic and commercial buildings [3], and has also been found to be an important part of low-energy adaptation responses to a warming

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climate under climate change [1,4]. In addition, thermal mass is a crucial part of wintertime passive heating, enabling heat gains accumulated during the day to be stored and released at night. Studies of the effectiveness of thermal mass for passive heating have reported heating energy savings of up to 9% [5,6].

In traditional buildings, thermal mass is typically provided from heavyweight materials such as brick, stone or earth-based materials, whereas in modern buildings the primary source of thermal mass is structural concrete [7]. Although inclusion of thermal mass in this way has thermal benefits, concrete generally has a higher embodied CO_2 (ECO_2) content than other types of structural systems for dwellings, notably timber frame construction. Concrete has been criticised on this basis and savings of 4–5 t ECO_2 from use of timber frame construction in a 100 m^2 detached house have been reported [8]. However, such figures do not take into account the potential savings in operational heating and cooling energy from the inclusion of thermal mass. For example, a review of comparative lifecycle analysis (LCA) studies of frame building materials in houses concluded that a decrease in overall CO_2 emissions can be achieved by focusing on the operational phase, rather than the construction materials [9]. Other studies have considered the impact of climate change on energy consumption or comfort [4,10,11]. However, none of these studies has quantified the impact of a warming climate on operational CO_2 emissions when comparing light and heavy-weight dwellings. This forms the basis of the LCA study detailed here, in which the performance of four houses that are essentially identical except for differing levels of thermal mass are compared over a 100-year period.

Specific questions to be addressed are:

1. Do heavier weight dwellings have potential to run at lower operational CO_2 emissions?, and if so:
2. What is the payback time, in terms of carbon emissions, to recoup any initial carbon investment in the thermal mass of the concrete building elements?
3. What are the overall carbon dioxide emissions saved over the building's lifecycle?
4. Is there an optimum weight of construction beyond which a point of diminishing returns is reached regarding operational versus embodied CO_2 savings?

The methodology used to address these questions is computer modelling of operational energy, using a multi-year dynamic thermal simulation combined with a detailed ECO_2 calculation for all building components in each case.

Four weights of thermal mass were considered:

1. Lightweight (timber frame with brick exterior).
2. Mediumweight (traditional brick and block exterior wall, with lightweight ceilings and partitions).
3. Medium-heavy (as mediumweight but with block partitions and concrete hollow-core ceiling on ground floor).
4. Heavy (heavyweight block inner leaf and partitions, with hollow-core concrete ceiling on the ground and first floor).

A full description of these cases together with the heating and cooling strategies to be used is given in Section 2. The climatic conditions used in the modelling were for the south-east of England under the UKCIP02 climate change scenario for

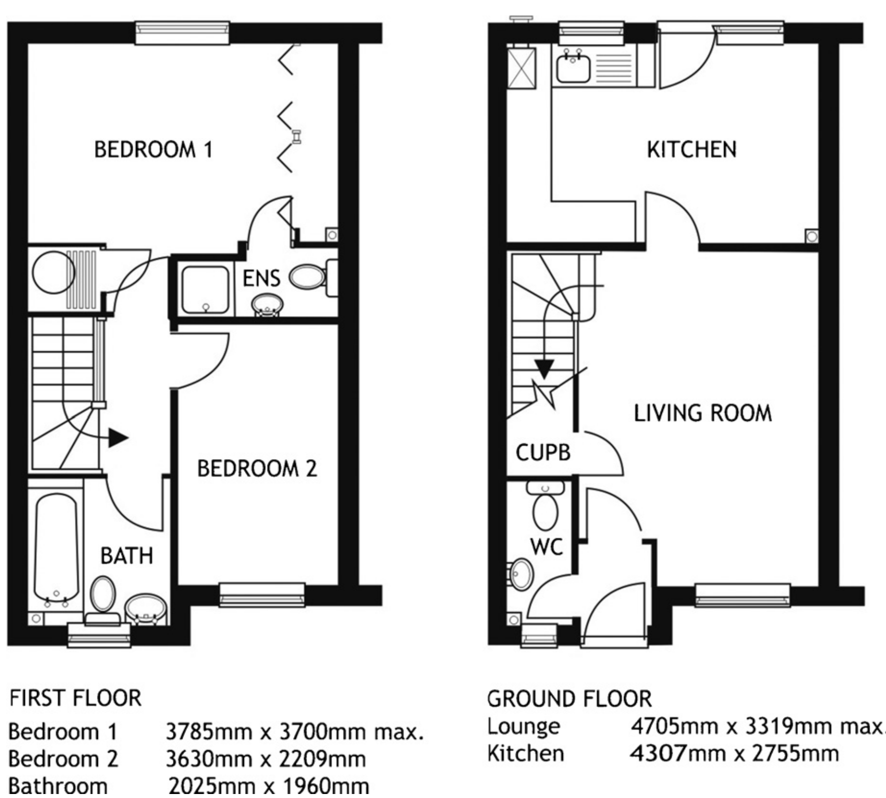

Fig. 1. Floor plans for case study dwelling.

medium-high emissions [12]. The development of weather data for the lifecycle analysis from this scenario is also explained in Section 2. The methodology and results for the operational energy and ECO_2 calculations are presented in Sections 3 and 4, respectively. The results are combined to provide 100-year lifecycle CO_2 emissions projections in Section 5 and conclusions are given in Section 6.

2. House specification

2.1. Construction

The case study building type considered was a semi-detached, two-storey, two-bedroom house: a typical starter home in the south-east of England. Floor plans and a schedule of façade and window areas are presented in Fig. 1 and Table 1, respectively. The total floor area of the building was approximately 65 m^2. The four different weights of construction (lightweight, mediumweight, medium-heavy and heavy) are described in Table 2.

The specifications have been standardised as far as possible (e.g. with the same external cladding, fenestration, roof construction and insulation materials) to remove any biases except from the differences in the structural frame or deliberate modifications to alter the extent of exposed thermal mass in the interior spaces. All four cases have construction standards commensurate with present-day good practice energy efficient housing in the UK. The U values of the construction were identical in all four cases, being—external walls: 0.27 W/m^2 K; windows and external doors: 1.30 W/m^2 K; ground floor: 0.20 W/m^2 K; roof: 0.15 W/m^2 K. Standards of air tightness were also taken to be the same. A background ventilation rate of 0.5 air changes per hour (ac/h) was assumed for maintenance of air quality.

No special considerations were made with respect to potential for passive solar heating in the heavier weight cases, and orientations and window areas are the same in each case. The heavyweight case is to some extent an unconventional construction type for the UK, but was included to show how a very high-level of thermal mass might compare in terms of operational energy use and ECO_2.

2.2. Occupancy

The house was assumed to be occupied by a family of two adults and one pre-school age child. The house was in continuous occupancy with one adult out during the day (08:00–18:00 h). Occupancy for the bedrooms was assumed to be 20:00–07:00 h for the child's bedroom and 23:00–07:00 h for the adult bedroom.

Table 1
Schedule of façade and window areas

Façade areas (including windows)	
	North = 24 m^2, east = 43 m^2 (no garage)
	South = 24 m^2, west = 43 m^2 (party wall)
Total window areas	
	North = 4.8 m^2, east = 0 m^2
	South = 5.0 m^2, west = 0 m^2 (party wall)
Orientation	
	The front of the building faces south

Table 2
Summary of case study building specifications

Case	Description
Lightweight	External walls: timber frame with plasterboard finish (inner leaf), insulation, ventilated cavity, brickwork cladding Internal partitions: timber stud with plaster board finish Ceilings: timber with plasterboard ceiling and chipboard floor finish Ground floor: solid concrete/screed Roof: timber/tile Flooring: carpet throughout, with exception of linoleum in bathrooms and kitchen
Mediumweight	As lightweight but with External walls: mediumweight concrete block[a] with plasterboard (inner leaf), insulation, ventilated cavity, brickwork cladding
Medium-heavyweight	As mediumweight but with Ground floor ceiling: pre-cast concrete floor units Ground floor partitions: mediumweight concrete block[a] with plasterboard finish
Heavyweight	External walls: heavyweight concrete block with fair-faced finish (inner leaf), insulation, ventilated cavity, brickwork cladding Internal partitions: heavyweight concrete block, fair-faced Ground and first floor ceilings: pre-cast concrete units Ground floor and roof construction: as other cases Flooring: carpet on first floor, with exception of linoleum in bathrooms and kitchen; stone tiles throughout ground floor

[a] In terms of admittance, mediumweight aggregate blockwork with a plasterboard finish is approximately the same as autoclaved aerated concrete (AAC) blockwork with a plaster finish [24,25]. The ECO_2 per unit volume of AAC blocks is also similar to mediumweight aggregate blocks.

2.3. Heating

In all four cases, heating was provided by a radiator gas-fired central heating system with a condensing boiler (85% efficiency). The heating set point was 19 °C in the bedrooms, 21 °C in the living room and kitchen and 22 °C in the bathrooms. The heating system was controlled to maintain the heating set points in all rooms, 24-h a day, except for the summer period June–August (inclusive), when the heating was shut down.

2.4. Cooling

Three possible modes of operation for cooling were examined. These are 'passive' (no mechanical cooling), 'air-conditioned' (mechanical cooling) and 'mixed-mode' (a hybrid of passive and mechanical cooling). A description of these

Table 3
Summary of passive, air-conditioned and mixed-mode control rules used

Cooling mode	Description of cooling mode for summer (June–September) period	Modified control rules for winter and mid-season October–May
Passive	External shading to achieve an 80% reduction in transmitted solar radiation through windows Natural ventilation of 6 ac/h provided whenever the operative temperature of the room is above the heating set point temperature if occupied, or 18 °C if not occupied, and the outside air is at least 2 K *cooler* than the room operative temperature. This last condition was to ensure that maximum ventilation was only provided at times when the outside air was a beneficial cooling source. At all other times, the ventilation reverts to the background level of 0.5 ac/h	If the room operative temperatures is more than 3 K above the heating set point (at which point the heating will be off) apply the summertime ventilation cooling rules to bring the temperature back to 3 K above the heating set point
Mechanical cooling installed according to criteria in Section 2.6		
Air-conditioned	Air conditioning using a whole house 'split-system' with one external unit (compressor) and four interior ceiling cassette units (fan coils). The cooling set points were 23 °C in the living room and kitchen and 21 °C in the bedrooms. These cooling set points are 2 K above the respectively heating set points. The bathrooms and stairs and landing were not directly serviced. Cooling was *only* provided when rooms were occupied	Air conditioning available through the year but with cooling set points 3 K above the summer. This is 5 K above the heating set point so there is little change of heating and cooling systems competing
Mixed-mode	The summertime natural ventilation and air conditioning rules above are applied, with the latter taking precedence. Note that because the effective cooling set points for the passive mode are the heating set points, there is 2 K 'band of opportunity' before the air conditioning becomes operational	The mid-season and winter natural ventilation and air conditioning rules above are applied, with the latter taking precedence. As for the summer case, there is 2 K band of opportunity before the two modes

cooling modes is given in Table 3. Cooling was available all year round, but modified control rules were used for the mid-season and winter period to avoid any conflict between the heating and cooling systems. Mechanical cooling was installed at a date determined from the thermal modelling using a criterion defined in Section 2.9.

For the passive cooling mode, a natural ventilation rate of 6 ac/h was assumed to be obtainable from window ventilation at all times of the year. In practice, this is likely to be a conservative estimate and higher natural ventilation rates may be possible through most of the year when windows are fully open. In the air-conditioned mode, the system was assumed to be run on mains electricity with a constant co-efficient of performance (COP) of 2.5. While operational COP ratings of around 3.0 are often quoted, the lower value used here was to reflect reduced COP's at part load which have been found to be as low as 1.1 in VRF systems [13].

2.5. Hot water services

Energy consumption and internal heat gains from hot water services were not considered in the assessment on the grounds that these can vary considerably between dwellings.

2.6. Other energy consuming items: lighting and appliances

The house was assumed to have low-energy light fittings in each room. In the modelling, lighting was controlled on a 'solar switch' whereby lighting was only provided when solar radiance to a room falls below a certain level. Heat gains from electrical appliances in the kitchen (from: oven, hob, washing machine, fridge-freezer, kettle and toaster (a tumble drier and dishwasher were not included)) and in the living room (television, VCR and digi-box receiver) were assigned based on surveys of typical usage patterns and energy ratings.

2.7. Energy mix

The energy sources and CO_2 emission factors assumed were:

- Heating – natural gas – 0.194 kg CO_2/kWh
- Cooling, lighting, appliances—national grid electricity, 0.422 kg CO_2/kWh

These figures are those used in the 2005 issue of the UK building regulations [14]. In the future it is inevitable that the fuel mix to the house will change. However, as it is not possible to say in what way, the choice was made to use the present-day emission figures.

2.8. Overheating targets (comfort)

In line with recent Chartered Institution of Building Services Engineers (CIBSE) guidance [15] the building was said to have overheated if in any 1 year 1% of occupied hours exceed 28 °C for living areas or 26 °C for bedrooms. The lower temperature threshold for bedrooms reflects the fact that people are generally more susceptible to thermal discomfort around sleep.

2.9. Criteria for the installation of mechanical cooling

The criteria used to determine the point at which mechanical cooling is installed was failure of the overheating target for a third year in any 5-year period either in the living room or the bedrooms. The cooling was installed in that third year.

This criterion is necessarily subjective as it is not possible to know how or when occupants would or would not choose to install air conditioning. The rationale for choosing this criterion was that under these conditions it would be reasonable for the occupants to suppose that summertime overheating would be more likely than not to occur in future years (e.g. >50% probability based on the experience of the last 5 years) so would choose to install air conditioning if that option were available.

2.10. Energy modelling software

The operational energy modelling was carried out using the dynamic thermal modelling program ENERGY 2 [16] developed at Arup. The program provides predictions for the operative temperature (which takes account of air and surface temperatures) in each room (room spatial average) at hourly resolution together with the energy consumption of the heating, cooling and lighting systems. Details of validation and inter-model comparison tests of ENERGY 2 have been published elsewhere [17,18].

2.11. Weather data

A key input to the energy modelling software is hourly resolution weather data. Here, weather data representative of the climate of suburban London was used based on a 20-year data set spanning the period 1976–1995 from Heathrow airport [19]. A 100-year data set, nominally for the period 2001–2100, was constructed by sequentially adjusting the 20-year data sequence for climate change under the UKCIP02 medium-high emissions scenario using the ‘morphing’ method [20]. The order of the years was not changed from that in the source data set and the 20-year set simply repeated in sequence under a ramped morphing factor.

While dynamic thermal modelling simulations of building energy typically make use of only one or two individual weather years, there can be substantial difference between years, particularly for summer peak temperatures, and so the method used here provides a more robust prediction for both averages and extremes of performance. While the modelling provides predictions at hourly resolution, the large amount of data makes graphical representation difficult and in the following section results are presented as averages over the five 20-year periods from 2001 to 2100.

3. Operational carbon dioxide emissions

3.1. Heating carbon dioxide emissions

Fig. 2 shows predictions for heating CO_2 emissions rates in each case, averaged over the five 20-year periods. The predicted emissions are less in the heavier weight cases relative to the equivalent lightweight case by 19% in the 2001–2020 period and 32% in the 2081–2100 period for the heavyweight case.

These differences are thought to be due to the benefits of passive thermal storage which enable daytime heat gains to be reused for heating at night. The relative differences are larger than the decreases of up to 9% reported elsewhere [5,6] but were found to be sensitive to the assumptions made regarding the heating schedule (e.g. 24-h continuous or intermittent heating), internal heat gains, and whether or not mid-season overheating was controlled. The more complex ways in which controls have been modelled in this study together with the heavier weights of thermal mass and different climate considered may be the reason for the larger relative decreases in heating energy.

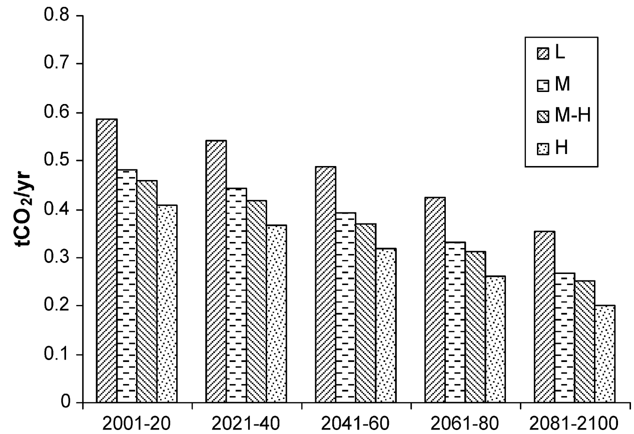

Fig. 2. Predicted CO_2 emissions from space heating averaged over 20-year periods.

3.2. Overheating

The occurrence of overheating in the passive only situation is shown through three overheating diagnostics in Fig. 3. Overheating becomes increasingly frequent in the latter half of the century. In the living room, occurrences of overheating decrease significantly with increasing thermal mass; both in terms of average overheating hours and extreme temperatures. Peak operative temperatures in the lightweight case are up to 5 °C higher than in the heavyweight case. The use thermal mass in bedrooms requires more caution because there is a risk of unwanted heat being retained in the fabric at night if ventilation rates are not sufficiently high. This effect is not seen here, however, and all three overheating diagnostics are lower in the heavyweight case, although there is substantially less variation than for the living room.

Table 4
Year of first failure of the overheating criteria with predicted years for installation of air conditioning shown in bold

		Year
Lightweight	Living room	**2021**
	Bedroom	**2021**
Mediumweight	Living room	2061
	Bedroom	**2041**
Medium-heavyweight	Living room	**2061**
	Bedroom	**2061**
Heavyweight	Living room	2081
	Bedroom	**2061**

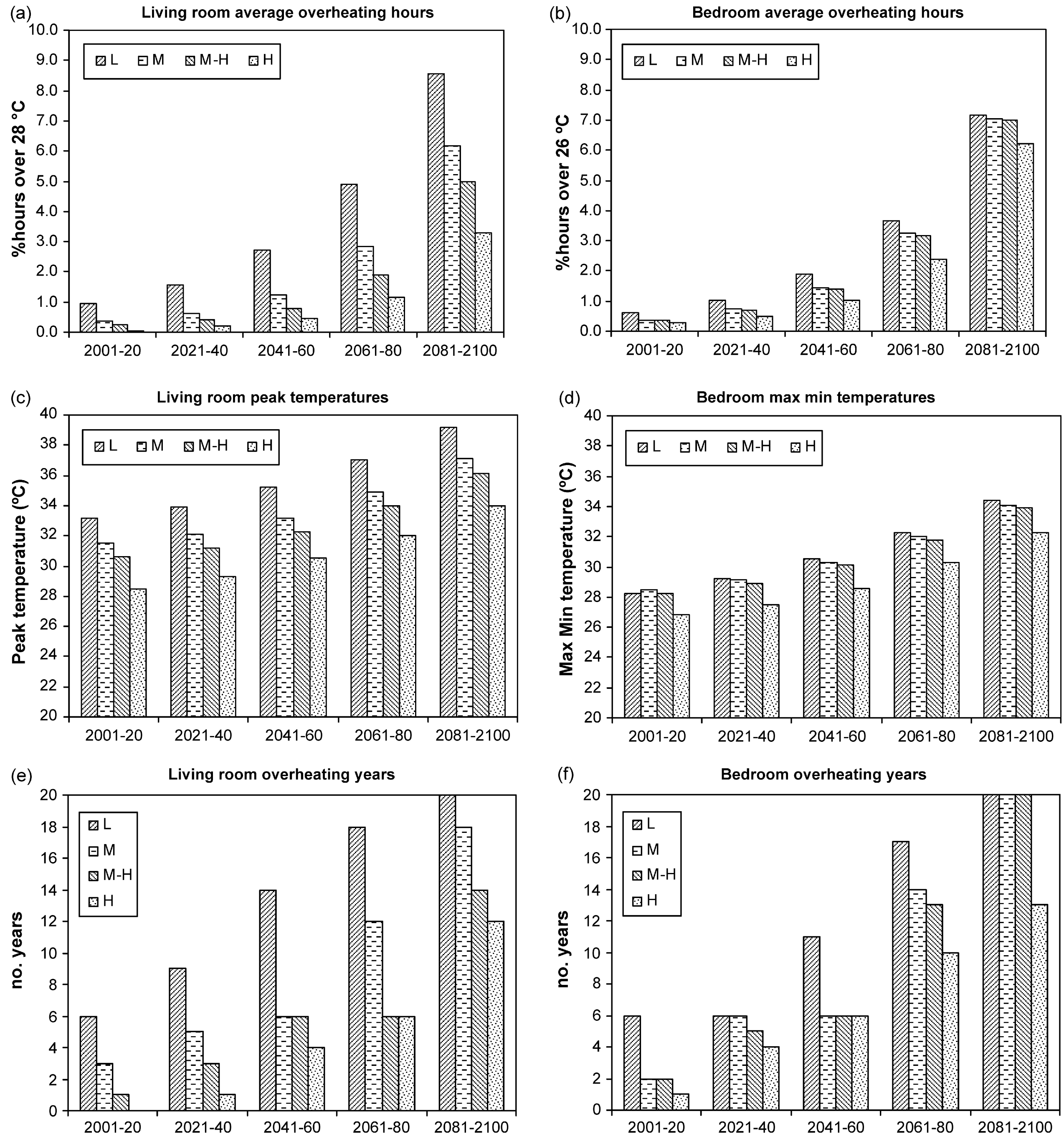

Fig. 3. Diagnostics of overheating for the living room and bedrooms, for each 20-year period. (a and b) Average overheating levels in terms of %hours over overheating temperature threshold. (c and d) Maximum predicted living room operative temperature in the living room and highest night time minimum temperature in the bedrooms. (e and f) Number of years failing the overheating criteria in each 20-year period.

The predicted years for the inclusion of air conditioning, determined according to the criterion define in Section 2.9, are given in Table 4. Under this criterion, air conditioning is projected to be installed in the lightweight case in 2021; 20 years later in the mediumweight case, in 2041; 40 years later, in 2061 in the medium-heavy and heavyweight cases. Note that the reason that the air conditioning installation year in all cases falls in the first year of a new 20-year data sequence is due to the nature of the underlying 20-year data set, which makes this the most likely point for the '3 in 5 year' criterion to be triggered.

3.3. Cooling carbon dioxide emissions

Fig. 4 shows the cooling energy CO_2 emissions for the fully air-conditioned and mixed-mode cases. When the air conditioning is first installed, in the lightweight case in the 2021–2040 period, emissions in the fully air-conditioned case are similar to heating CO_2 emissions and increase thereafter. The emissions in the heavier weight cases are somewhat lower, which is interpreted as being due to thermal mass reducing the number of hours for which cooling is required, but the

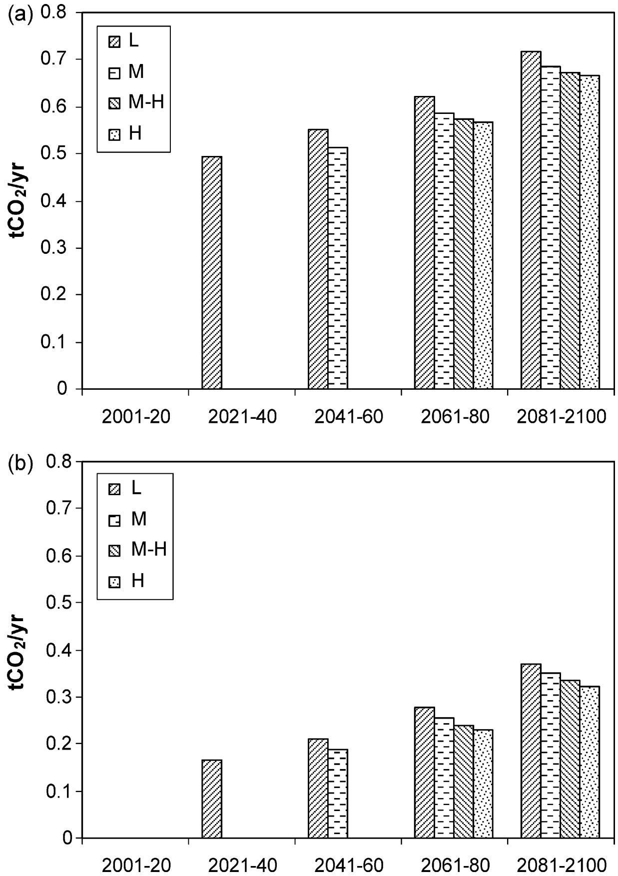

Fig. 4. Carbon dioxide emission rates from use of the air conditioning system, average over 20-year periods, for (a) the fully air-conditioned case and (b) the mixed-mode case.

difference decreases as the century progresses and the climate gets warmer. The emissions for mixed-mode control are substantially lower in all cases, indicating that the way the system is used and the building operated will influence energy use. However, in the fully air-conditioned and mixed-mode cases, the key impact of the thermal mass is to delay the point in the lifecycle at which air conditioning is likely to be installed.

3.4. Lighting and appliances

The predicted lighting energy carbon emissions, averaged over the 100 years, were 0.15 t CO_2/year, and did not vary appreciably. The appliances energy carbon emissions were a constant 0.73 t CO_2/year.

4. Embodied carbon dioxide emissions (ECO_2)

4.1. ECO_2 intensities of materials

The ECO_2 intensity (mass of embodied carbon dioxide per unit mass of material, usually expressed as kilograms of CO_2 per tonne of material (kgCO_2/t)) for each material was obtained from the Institution of Structural Engineers (IStructE) publication *Building for a sustainable future* [21] which is a widely used source of ECO_2 data in the UK, but with the following exceptions:

- *Timber, plywood and chipboard*. The IStructE ECO_2 intensities for timber, plywood and chipboard were 1644, 1465 and 2560 kgCO_2/t, respectively. Other values for the ECO_2 intensity of timber quoted in the literature vary across a wide range, from positive to negative. The IStructE value lies at the upper end of this range and so were reviewed. The authors were unable to obtain an alternative verified value, but a value of 400 kgCO_2/t was estimated for timber, inferred from ECO_2 intensities for timber frame and masonry external wall constructions published by the UK Building Research Establishment (BRE) [22]. This value is believed to be a fair representation of cradle to grave timber sourced from modern sustainable forestry. The same value was also used for plywood and chipboard, although may be an underestimate for these materials.
- *Concrete blocks*. The IStructE guidance provides a single ECO_2 intensity for concrete block of 203 kgCO_2/t. Based on published BRE figures, it is believed that this value relates to autoclaved aerated concrete (AAC) blocks rather than aggregate blocks which were used in the modelling. Consequently, the following ECO_2 information provided by BRE [23] was assumed for aggregate blocks:
  - *Mediumweight block*: 120 kgCO_2/t
  - *Heavyweight block*: 75 kgCO_2/t.

  Whilst AAC blocks were not used, the ECO_2 intensity per unit volume of this material is similar to traditional mediumweight blocks and the thermal characteristics are also similar when compared to aggregate blocks with a plasterboard finish [24,25].
- *Hollow-core concrete ceiling slab*. The IStructE guide gives a value of 208 kgCO_2/t for precast concrete. This figure has been revised slightly to 200 kgCO_2/t based on information provided by BRE [23] specific to hollow-core floor units.
- *Wall insulation material*. The IStructE guidance provides only a single value for the ECO_2 intensity of wall and roof insulation materials, of 2606 kgCO2/t. This value was taken to be representative of fibreglass quilt insulation and was used for the roof insulation in all four cases. However, this material is not commonly used for timber and masonry cavity walls. The ECO_2 of exterior wall sections was found to vary appreciably according to choice of insulation material, and in order to provide a fair comparison between cases, a common material was chosen. This was a rigid phenolic foam board. Based on personal communication with the European Phenolic Foam Association [26], an ECO_2 intensity of 5700 kgCO_2/t was estimated for this material.

4.2. Materials inventory and results

A detailed inventory of all the materials incorporated in the structure and finishes of the houses was assembled and total ECO_2 values calculated. The reason for using a comprehensive inventory was to enable the contributions from all the

Table 5
Summary of ECO_2 (t) at completion for the four case study weights

	Lightweight	Mediumweight	Medium-heavyweight	Heavyweight
Common elements (all cases)	28.16	28.16	28.16	28.16
Common elements (light, medium and medium-heavy)	2.59	2.59	2.59	
Additional	1.28	2.52	4.30	8.80
Total	32.03	33.27	35.05	36.96
Difference to lightweight	0.00	1.25	3.03	4.93

individual elements to be placed in context. The material components of the buildings were broken down into the following classifications:

- elements common to all four cases, including roof structure (timber and tile), brickwork cladding, ground floor construction, fenestration and external doors(U-PVC), internal doors (timber), staircase (timber), first floor carpets, electrical, water and heating services components;
- elements common to the lightweight, medium and medium-heavyweight cases, principally plasterboard finishes, internal partitions, ceilings and ground floor carpets;
- elements specific to the individual cases: these are primarily due to the different wall and ceiling constructions and wall and ground floor finishes (in the heavyweight case).

The calculated ECO_2 for these different categories are given in Table 5. By far the largest contribution is from the common elements, which constituted just over 28 t CO_2. The total ECO_2 content is larger in the heavier weight cases, being 1.25, 3.03 and 4.93 t CO_2 more than the lightweight value for the medium, medium-heavy and heavyweight cases, respectively. These values are broadly consistent with the value of 4–5 t CO_2 quoted by the timber industry for a larger 100 m^2 detached house [8].

As well as the material quantities at the point of construction, ECO_2 contributions from refurbishment of finishes, services, doors and fenestration were also estimated. Values ranged from 19 t CO_2 (heavyweight case) to 26 t CO_2 (lightweight case). The lower value for the heavyweight case was primarily due to the different ground floor finishes (stone tiles rather than carpet), which constituted 5.5 t CO_2 of the difference, and the fewer replacement cycles for air conditioning plant (assumed to occur every12.5 years [27]) which constituted 1.5 t CO_2 of the difference. Due to the sensitivity to floor coverings and the complexities of representing the data for the different refurbishment intervals, refurbishment ECO_2 has not been included in the total lifecycle values presented in the following section. However, it is noted that according to the calculations made, to do so would be to favour the heavier weight cases.

5. Lifecycle carbon dioxide emissions

Fig. 5 shows the total cumulative CO_2 emissions, year-on-year for the 100-year lifecycle, for the four weights of construction in the air-conditioned and mixed-mode cases. Because the initial ECO_2 increase with weight of construction but the operational emissions reduce, in all cases there is a point where the lines cross. This point indicates the 'carbon payback' time for the initial investment in the additional thermal mass. Table 6 gives the carbon payback times relative to the lightweight case for the heavier weight cases, which range from 11 to 25 years. For the mediumweight case, carbon parity with the lightweight case is obtained before the air conditioning is installed in the lightweight case, indicating that the savings in heating energy alone are solely responsible for obtaining carbon parity in this case. The different points at which air conditioning is installed do however affect the location of the other cross over points and the emissions savings thereafter. The total emission savings predicted relative to the lightweight case are summarised in Table 6.

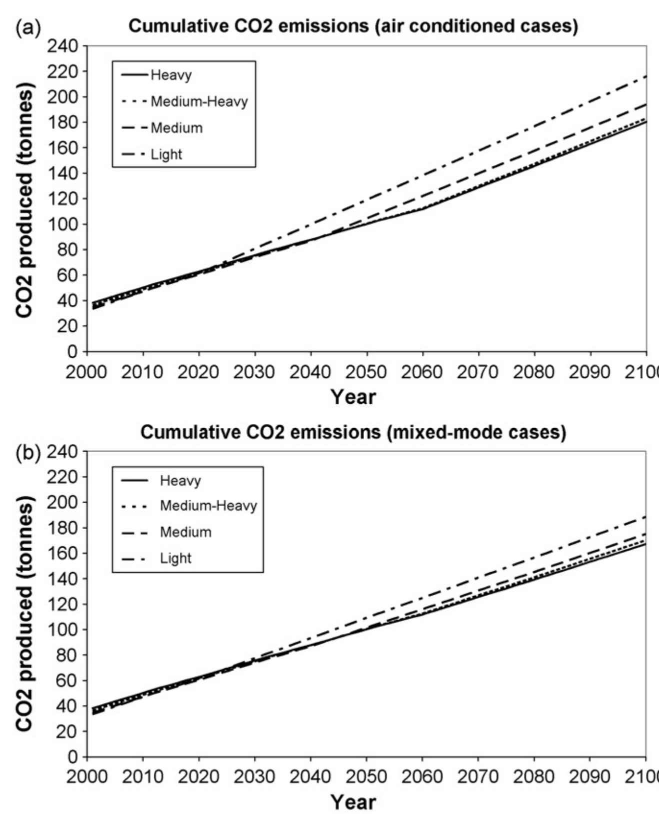

Fig. 5. Cumulative carbon dioxide emission from ECO_2 and operational energy for (a) the fully air-conditioned case and (b) the mixed-mode case.

Table 6
Predicted 'payback' periods over which operational emissions savings offset initial ECO_2 differences, and predicted total lifecycle CO_2 savings relative to the equivalent lightweight cases

Case	ECO_2 payback time (years)		CO_2 saved over 100-year lifecycle (t CO_2) and %of equivalent lightweight case (in parenthesis)	
	Mixed-mode	Fully air-conditioned	Mixed-mode	Fully air-conditioned
Medium	11	11	13.5 (7%)	22.0 (10%)
Medium-heavy	21	21	18.4 (10%)	33.0 (15%)
Heavy	23	25	21.3 (11%)	35.7 (17%)

6. Conclusions

Specific conclusions to the four questions posed in Section 1 are:

1. The heavier weight cases all showed reduced operational CO_2 emissions with the largest benefits being found for the heaviest weight considered. This was primarily due to the dynamic thermal storage provided by the thermal mass improving the energy efficiency of both heating and cooling modes of operation and also, importantly, improving the passive summertime performance, thereby delaying the point in the lifecycle at which occupants might be likely to seek to air condition their homes.
2. The initial ECO_2 of the constructions was larger in all the heavier weight cases, but by a relatively small amount in the context of the total lifecycle emissions. The payback time for the mediumweight case was only 11 years. This was solely due to savings in heating energy and therefore relatively insensitive to the climate change scenario. The payback times for the medium-heavy and heavyweight cases were between 21 and 25 years and were affected by the time horizon for the installation of air conditioning in the lightweight case and so were sensitive to climate change scenario.
3. All the heavier weight cases were found to have lower CO_2 emissions than the equivalent lightweight timber case, ranging from a 7% saving (mediumweight mixed-mode case) to a 17% saving (heavyweight fully air-conditioned case).
4. No clear 'optimum weight' of construction was found at which initial ECO_2 investment outweighed lifecycle operation savings under the climate change scenario used, with the heavyweight case showing best performance under all the indicators examined.

Dwellings being built today should be designed to have operational lifetimes of several decades and ideally longer given current rates of house building in the UK, making the impact of climate change an important design consideration. The results presented here indicate that when considering dwellings adapted for warmer summers using passive and active measures, medium to heavyweight construction is likely to provide more potential for achieving higher levels of indoor comfort and reduced lifecycle CO_2 emissions.

The results presented here relate to a particular dwelling, for which reasonable assumptions have been made for variables such as heating schedules, occupancy patterns, internal heat gain levels, building orientation and mechanical system characteristics and set points. Further research is needed to better understand the influence of the various design variables. There is also need for better data regarding the ECO_2 intensity of different building materials and to reduce these across the board, although it should be noted that the timber and concrete components of a typical new UK house were found to be only modest contributions to the overall ECO_2 content of the building. In this paper, we have also only considered one domestic building of given size and form. Buildings of different form and usage type have different requirements for ventilation, heating and cooling, particularly in different sectors, e.g. schools, hospitals and offices, and further research is needed to the establish the relative merits of thermal mass with respect to lifecycle CO_2 emissions in those cases. However, the results presented here are indicative of the lifecycle CO_2 savings and other performance benefits that can potentially be achieved by using heavyweight structural elements to provide thermal mass in housing under present-day and projected future climates for the UK.

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