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Integrating effects of overheating on human health into buildings' life cycle assessment

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Abstract

Purpose Due to climate change, the severity and length of heat waves are increasing, and this trend is likely to continue while mitigation efforts are insufficient. These climatic events cause overheating inside buildings, which increases mortality. Adaptation measures reduce overheating but induce environmental impacts, including on human health. This study aims to integrate the overheating-related effects on human health in building LCA to provide a design aid combining mitigation and adaptation.

Methods In a novel approach, an existing building LCA tool is utilised to evaluate life cycle impacts, including damage to human health expressed in DALYs. The overheating risk is then evaluated using an existing dynamic thermal simulation (DTS) tool and prospective climatic data. Overheating is expressed as a degree-hour (DH) indicator, which integrates both the severity (temperature degrees over a comfort threshold) and the duration (hours). By assuming proportionality between DALYs and DH × area in a first step, the 2003 heat wave mortality data, 2003 climatic data, and a simplified model of the national residential building stock were used to identify a characterisation factor, which can then be used to evaluate DALYs corresponding to any building using DH obtained by thermal simulation.

Results The proposed overheating model not only allows to derive a characterisation factor for overheating to be used in building LCA but also provides practical insights. The first estimation of the characterisation factor is 1.35E-8DALY. DH-1.m-2. The method was tested in a case study corresponding to a social housing apartment building in France built in 1969 without insulation. The thickness of insulation implemented in the renovation works was varied. For this specific case study, the contribution of overheating is significant, ranging from 1.1E-5DALY.m-2.y-1 to 2.2E-5DALY.m-2.y-1, comparable to the contribution of heating. DTS and LCA results found an optimal thickness, minimising the human health indicator in DALYs. This underscores the potential of active cooling to reduce human health impacts, especially if it consumes electricity produced by a photovoltaic system integrated in the building.

Conclusion Combining DTS and LCA makes it possible to evaluate damage indicators on human health, including building life cycles (e.g., material and energy) and overheating-related impacts. An application on a case study shows this method's feasibility and gives a first order of magnitude of overheating health impacts induced by buildings. A more sophisticated model could replace the assumed proportionality between DALYs and DH.

Keywords Building · Overheating · Mitigation · Adaptation · DALY

1 Introduction

As climate changes, heat waves increase in intensity, frequency, and duration (Tebaldi et al. 2006), significantly affecting human health (Peng et al. 2011; Mitchell et al. 2016). This underscores the crucial role of researchers, architects, urban planners, and policymakers in adapting buildings to ensure sufficient comfort during increasingly severe heatwave periods. The challenge is to achieve this objective at a lower cost and with a lower environmental impact in new construction, but even more so regarding the existing stock.

Thermal comfort is evaluated using numerical simulation if future climatic conditions are considered or improvement measures are studied. Solutions are studied regarding buildings (Mavrogianni et al. 2012) and urban micro-climates (Kolokotroni and Giridharan 2008).

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Environmental impacts are assessed using LCA (Ortiz et al. 2009; Cabeza et al. 2014; Anand and Amor 2017). Active solutions (air conditioning) induce environmental impacts due to the fabrication and energy use of cooling systems. Passive solutions include solar protection, night ventilation, increasing thermal insulation (Peuportier 2004; Porritt et al. 2012), and thermal mass (Peuportier and Thiers 2009). Such solutions improve thermal comfort: opening windows at night cools the walls and slabs during hot summer and mid-season, solar protection and high insulation reduce heat transfer, and thermal mass reduces temperature fluctuation, limiting overheating. On the other hand, the fabrication of shading systems, insulation, and masonry induces environmental impacts.

Few studies have gone so far as to evaluating damage to human health due to overheating, for instance, expressed as loss of life expectancy, such as in Ibbetson et al. (2021) in the particular case of care home residents. Separate evaluation of comfort and environmental impacts does not allow for ranking different solutions, e.g., air conditioning may improve thermal comfort but reduce environmental performance compared to a passive solution. The innovation proposed in this article combines thermal comfort and LCA evaluations using a single indicator related to human health. Such a damage indicator exists in impact assessment methods like ReCiPe (Huijbregts et al. 2017) or Impact World+ (Bulle et al. 2019). The new development presented corresponds to an evaluation of damage due to indoor overheating. The combined indicator accounts for the effect of overheating on mortality and also life cycle-related impacts, including contributions of material fabrication and energy consumption linked with ReCiPe2016 impact categories (Particulate Matters, Tropospheric ozone formation, Ionizing radiation, Stratospheric ozone depletion, human toxicity, global warming, and water use).

The goal of LCA studies based on this development is to help designers choose and size architectural and technical solutions according to climate conditions, planned use, and building comfort level objectives. The proposed actions (see, e.g., Gupta and Gregg 2012) may concern:

- The microclimate with actions on trees, greening of facades or roofs (Gromke et al. 2015), cooling road surfaces in summer to store heat in the ground and use it in winter is mentioned (Albers et al. 2015), use of reflective roofs and road surfaces (Akbari and Mathews 2012; Synnefa et al. 2012),
- The envelope with solar protection, insulation, coverings (Akbari and Matthews 2012), thermal mass (Kendrick et al. 2012; van Hooff et al. 2014),
- Ventilation with nocturnal over-ventilation (Dupin et al. 2014), ground heat exchangers,
- Systems with air fans, cooling, air conditioning, evaporative cooling (Smith et al. 2011; Maillard et al. 2014; Montazeri et al. 2015; Pomianowski et al. 2015),
- Or the occupants with windows opening, managing solar protection, or limiting internal heat gains.

In the case study presented in this article, only aspects related to the envelope (e.g., insulation) and ventilation are addressed, but the methodology could be applied to the other aspects. Drinking water and using a cooling spray can also be advised, but some older adults do not effectively follow such advice. Improving building performance through appropriate design is part of a prevention approach addressed in the LCA study proposed here. This prevention approach is spread over the long term because buildings are long-lasting. Overheating is likely to increase due to climate change; therefore, the proposed evaluation method should allow prospective climate data to design buildings adapted to future conditions.

This article proposes a first simplified evaluation method, aiming at estimating an order of magnitude of the effect of overheating on human health and comparing it with other LCA contributors considering the same damage indicator. If the effect of overheating is significant, refining this method would be relevant. A case study is used to perform this estimation and comparison. The goal of the LCA study is expressed above; the following chapter on Section 2 presents the scope of the study, inventory (integrating a new elementary flow regarding overheating), impact assessment (integrating an interim characterisation factor), and the case study. This case study only illustrates the method, which can be applied to any building. Results are shown in the next chapter, followed by a discussion, conclusions, and perspectives.

2 Material and methods

The proposed method complements a usual Building LCA by integrating the impacts of overheating on human health. Overheating is evaluated using climatic data as input for dynamic thermal simulation, and an elementary flow is derived, complementing the usual life cycle inventory. Impact assessment is then performed using an interim characterisation factor based on mortality data from 2003 in France. The methodology can be applied in other contexts considering various climates, construction techniques, and occupants' behaviour. Materials, water, and energy-related impacts are evaluated considering the damage to human health indicator defined in the ReCiPe 2016 impact assessment method (Huijbregts et al. 2017). The overall framework is summarised in Fig. 1 below. The upper part corresponds

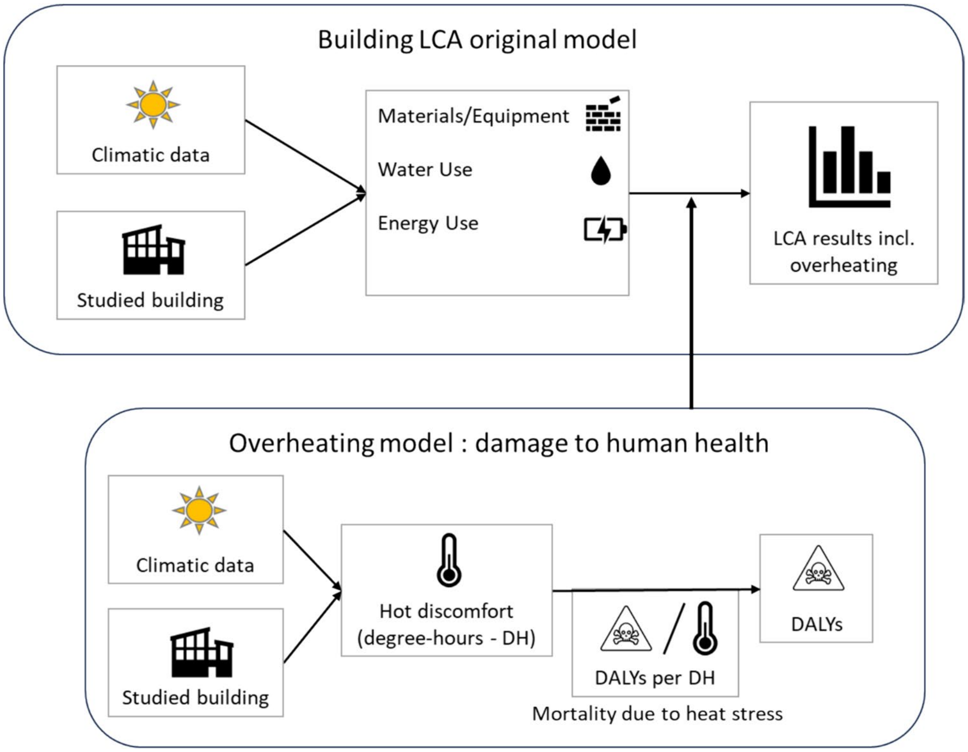


Fig. 1 Overall framework

to a usual Building LCA. The proposed complement is illustrated in the lower part. The following paragraphs present the scope, inventory, and impact assessment steps; the last is a case study description.

2.1 Scope of the study

The study addresses the adaptation of buildings to climate change and does not aim at capturing all impacts of a heat wave. For instance, it does not include outdoor workers. According to Santé Publique France (French health agency), only four excess deaths correspond to workers (Santé Publique France 2019), to be compared to the total excess deaths of 1480 the same year, and no outdoor excess death was mentioned in the INSERM (French medical research institute) report regarding the year 2003 (Hémon and Jougla 2004). Possibly, more deaths could be attributable to outdoor workers. However, not enough data are available to account for this aspect.

The impacts of a building project on human health can be evaluated using a life cycle assessment (Jolliet et al. 2015), which is now defined, e.g., in European standards regarding products (CEN 2019a) and buildings (CEN 2012). These standards evaluate impacts on human health by integrating various impact categories, e.g., particulate matter, ozone, and toxicity, using, for instance, the Comparative Toxic Unit for humans (CTUh) expressed as cases. Such indicators, e.g., depending on the number of illness cases generated by pollutants, are inappropriate for overheating. We have therefore used a similar damage indicator in Disability Adjusted Life Years (DALYs) as proposed by Murray (1994) and Murray et al. (2020), which is integrated into the life cycle impact assessment methods ReCiPe 2016 (Huijbregts et al. 2017) and added overheating as an interim additional impact category.

The studied system corresponds to a residential building over a reference study period, with the exact boundaries as in a usual Building LCA approach, e.g., following the EN 15978 standard. The only difference is related to an aspect included in the definition of the functional unit regarding the level of indoor thermal comfort. Overheating can vary when comparing alternatives: a maximum temperature is not fixed, and the building is not necessarily equipped with air conditioning. Air conditioning induces impacts related to fabrication, transport, energy use, and end-of-life processes but reduces impacts on human health due to overheating. The approach presented in this article evaluates such a balance and other technical solutions like thermal insulation. Assumptions are specified in the following inventory and impact assessment, and limitations are addressed in Section 4.

The building life cycle assessment tool Pleiades ACV EQUER (Polster et al. 1996) and ecoinvent v3.4 LCA data (Frischknecht and Rebitzer 2005; Weidema et al. 2013) were used to evaluate impacts related to the fabrication, replacement, and end of life of construction products and equipment, as well as energy and water consumption during operation. The operational energy consumption and indoor temperatures were evaluated using Pleiades STD COMFIE (Peuportier and Blanc Sommereux 1990). STD COMFIE was chosen because it is linked to an LCA tool, and the thermal model was studied in several validation studies, e.g., Brun et al. (2009) and Munaretto et al. (2017).

Because buildings are long-lasting systems, numerous studies have addressed the impact of climate change in terms of heating and air conditioning needs, for example, in Switzerland (Frank 2005), in Great Britain (Hacker et al. 2008; Collins et al. 2010; Kolokotroni et al. 2012; Williams et al. 2012), The Netherlands (van Hooff et al. 2014), in Australia (Wang et al. 2010), in the United Arab Emirates (Radhi 2009), and in China (Wan et al. 2011). A similar approach, based on prospective climatic data, was applied in our study.

2.2 Inventory

Like in a standard building LCA, materials, systems, transport, energy, and water use are quantified, and datasets are collected in databases, as explained above. An additional elementary flow is suggested below to integrate the effects of overheating.

Heat waves are characterised by duration and severity: the sum of temperature exceedances above a threshold over the duration (Gosling et al. 2014; Brown 2020). It is proposed to characterise indoor overheating using a similar severity characteristic, noted DH (degree-hours), integrating both temperature exceedance and duration. The assumption behind this indicator is that, e.g., a 2 °C temperature exceedance during 1 h induces the same damage to human health as a 1 °C exceedance during 2 h (see Section 4). In this first simple approach, damage to human health is proportional to DH. A non-linear model could be studied as a perspective. Humidity is not accounted for in our study, though it can be proposed as a perspective.

The temperature exceedance is related to a threshold. This threshold could be a fixed temperature, for example, 28 °C (Porritt et al. 2012), or vary according to an adaptive comfort approach (van Hooff et al. 2014). To consider people's habituation of heat, we have chosen an adaptive comfort approach based on the standard EN 16798-1 (CEN 2019b). By this standard, the hot discomfort threshold temperature considered is calculated at each time step (1 h in this study) based on the daily rolling average outdoor temperature (see Fig. 2).

For instance, if the average outdoor temperature of the previous day was under 16 °C, the threshold is 26 °C, and it rises to 28 °C if the average outdoor temperature is above 22 °C. The hot discomfort limit temperature may be modified in the presence of systems that modify the occupants' thermal sensation (by creating air speed, adding or reducing air humidity, etc.). It is also considered that discomfort affects human health only if the indoor space is occupied (e.g., at night for a bedroom). Occupancy schedules are defined according to the use of each thermal zone. A thermal zone corresponds to a part of the building, gathering spaces with similar thermal behaviour (i.e., same use, same orientation), e.g., north-oriented classrooms, corridors, south-oriented offices, etc.

The calculation of this DH indicator consists of summing the hourly difference between the zone's operational

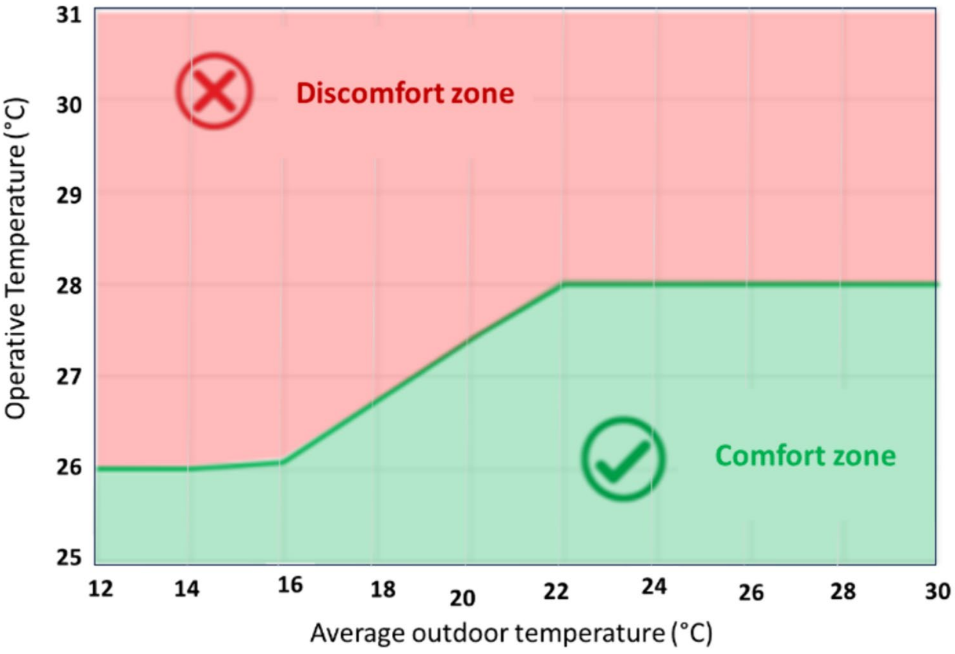


Fig. 2 Threshold discomfort temperature in terms of the average outdoor temperature of the previous day

temperature and the discomfort threshold over the occupancy period during a summer period. The operational temperature integrates air and wall temperatures to account for convective and radiative heat transfer, which influences the comfort sensation of occupants and possible health risks.

The evaluation of temperature profiles requires the implementation of more precise models than the evaluation of energy consumption. The comparison of models then showed that oversimplified tools (for example, the French thermal regulation calculation based on one time constant) deviate significantly from validated tools (Peuportier et al. 2011). Dynamic thermal simulation is therefore used in this study.

Studying the adaptation of buildings to climate change requires the availability of appropriate climate data (Guan 2009). Dynamic thermal simulation tools generally use data over a year at hourly intervals: temperature, solar radiation, wind, humidity, etc. It is, therefore, not enough to only know the annual average temperature increase. Previous studies used climate projections (Kershaw et al. 2011; Jenkins et al. 2015). A collaboration with the French meteorological research centre allowed prospective climate data to be developed for French climates, particularly the Greater Paris Area considered in this study. The highest greenhouse gas emissions scenario, RCP8.5 (Representative Concentration Pathway, radiative forcing 8.5 W/m2), was considered. Because dynamic thermal simulation models need hourly meteorological data and to take into account the urban signal, we used very high-resolution climate simulations (2.5 km) carried out with the AROME climate model (Daniel 2017; Fumière et al. 2020; Caillaud et al. 2021) combined with the TEB (Town Energy Balance) urban diagram (Masson 2000). AROME simulations are also produced by dynamic downscaling (Seity et al. 2011; Voldoire et al. 2013). Two time periods were simulated, corresponding to a near future (2041–2050, 10 years) and a distant future (2080–2099, 20 years).

The approach of a “Typical Meteorological Year” is chosen to recreate a year considered typical of the future climates (Hall et al. 1978). The principle of the approach consists of extracting, for a given month, the most “typical” year for that particular month. For example, from observations from 1991 to 2020, January 1999 is the closest to the average of all January, February 2004 is the closest to the average of all the months of February, etc. By concatenating the 12 months extracted, we obtain a 1-year series whose monthly averages are as close as possible to the averages for the period.

The average year reconstructed by the “Typical Meteorological Year” method makes it possible to represent average future climatic conditions while considering inter-day variability. However, it does not allow extreme events to be considered. Based on the two indicators mentioned above, length and severity, two types of heat waves are defined:

- A median heat wave which corresponds to the heat wave simulated by AROME whose duration (in number of days) and severity are the closest to the median of the duration and severity of the events;
- An extreme heat wave corresponding to the closest heat wave to quantile 95 of the set of events.

Extreme and median heat waves are selected according to duration and severity characteristics that account only for temperature, not humidity and solar radiation. However, humidity and solar radiation data are included in the climate data used as input in the thermal simulation of buildings.

Choosing between a near or distant future and a median or extreme heat wave could be left to the user’s decision, depending on the study objectives. It could also be used to evaluate uncertainty on the degree-hour evaluation due to temporal (near to distant future) and intrinsic (median, extreme) variability of the heat waves’ intensity and duration. As the goal is here to evaluate the significance of overheating compared to other contributions to damage to human health, a worst-case scenario with extreme heat waves and a distant future was selected in the case study.

The damage caused by overheating to human health depends on the number of occupants in the studied building. At the design stage, this parameter is unknown. For instance, an apartment can be designed for a four-person family, but after some time, the children leave home. It is, therefore, current practice in building design to consider a typical number of occupants according to the net living area, e.g., 25 m^2 average area per person. The net living area is the floor area, excluding walls and spaces like cellars, parking places, and attics. A linear model is considered in this first simplified approach: the damage is proportional to the net living area, noted A. The damage is assumed to be proportional to both DH and A, and the elementary flow considered is DH.A, expressed in $K.h.m^2$.

2.3 Interim characterisation factor and impact assessment

The life cycle impact assessment method ReCiPe 2016 (Huijbregts et al. 2017) was used in the standard Building LCA part of the study. All impact categories contributing to damage to human health in the ReCiPe2016 method were evaluated. An additional category for overheating was added using a characterisation factor described hereunder and applied to the DH.A elementary flow.

Using detailed mortality data from the 2003 heat wave in France associated with a simple model of the French 2003 building stocks, an interim characterisation factor for damage to human health due to overheating is derived, as explained in Fig. 3.

First, the number of DALYs attributed to the 2003 heat wave was evaluated. Then, a simple model of the 2003 building stock was built based on eight archetypes with corresponding areas A. Finally, thanks to dynamic thermal simulation, the degree-hour of discomfort (DH) per archetype was determined based on the climatic data from 2003. This allowed to express a ratio of DALY/DH.A, which can then be used as a characterisation factor in building LCA.

2.3.1 Evaluation of DALYs for the 2003 heat wave

The National Institute of Statistics in France evaluated the excess deaths from the 2003 heat wave to 15,300 deaths (INSEE 2020) from 1 to 24 August. According to mortality monitoring, the fatalities returned to normal after the heat wave until the end of 2003 (Hémon and Jougla 2004). The expected number of deaths is evaluated based on 4 years: from 1999 to 2002. In past years, an average of 31,700 deaths were reported over the same period, against 47,000 in 2003. No significant excess of deaths was reported during the rest of the 2003 summer. The number of excess deaths is provided for different age intervals (see Table 1).

In this study, we use a “reference age” of 78 to evaluate the number of years of life lost. This figure was obtained by calculating the average age at death in 2003, as life expectancy depends on the birth year and was lower in the twentieth century than today. Using a life expectancy could lead to underestimating the number of years of life lost.

Following this procedure, an excess death at 77 years old would lead to 1 year of life loss, and so to 1 DALY as non-lethal diseases could not be included in this first study due to lack of data: this topic constitutes a research perspective. For instance, if during a heat wave occurring year y, the number of excess deaths is n in the age interval between 65 and 74 and the considered reference age is 78 years, the corresponding number of DALYs is evaluated as $n.\ (78-(65+74)\ /\ 2)$. Possible confounding factors and interaction between overheating and other health problems are not considered in this first simplified method (see Section 4). A total DALY indicator is derived by adding the contribution of the different age intervals below the reference age. From the excess deaths evaluated by the French National Statistical Institute (INSEE 2020) for each age range, the total number of DALYs (41,056) due to the 2003 heat wave was derived as detailed in Table 1 below and based on the following equation for each age range:

Table 1 Excess deaths and corresponding DALYs

Age range (years)	Average age	Excess deaths	DALYs
50 to 64	57	1178	24740
65 to 74	69.5	1499	12745
75 to 77	76	1785	3571
Total		4763	41056

$$\mathrm{DALYs} = (\mathrm{ReferenceAge} - \mathrm{AverageAgeAtDeath}) \times \mathrm{ExcessDeath}$$

This finally leads to an average of 9.2 years of life loss for deceased persons under 78 because of the heat wave.

2.3.2 2003 Building stock model

The French Environment and Energy Agency (ADEME 2006) describes the French building stock of 2005, which is expected to be close to the 2003 stock, especially the number of principal residences (25.8 million), individual houses (17.3 million), and collective dwellings (13.4 million). Archetypes are often defined to represent a stock of buildings (Mavrogianni et al. 2012). This method was applied, considering the following archetypes: houses and apartment buildings with three construction periods.

These construction periods were identified using data from the CEREN (Center of Study and Research on Energy Economics) and linear interpolation from 1999 to 2003 (CEREN 2006). Following this description of the building stock, eight archetype models were built for each construction period, including individual houses and collective dwellings, as detailed in Table 2. Refining this building stock model can also be a perspective.

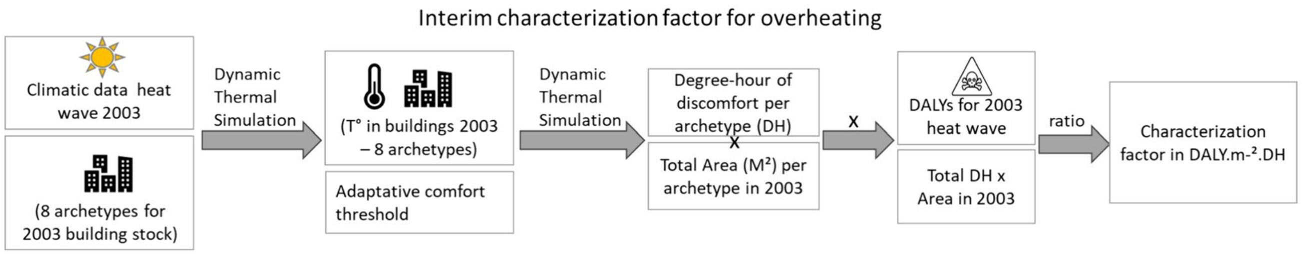


Fig. 3 Interim characterisation factor development

Table 2 Building archetypes in the building stock model

Construction period	Individual house (IH)	Collective dwellings (CD)
Before 1975	IH_75: Old stone house, single glazing, not insulated	• CD_H_75: Haussmannian apartment buildings (not insulated, single glazing) • CD_HLM_75: non-insulated social housing apartment buildings (not insulated, single glazing)
1975–1998	IH_98: 1950 house renovated, single glazing, 5 cm of insulation	• CD_H_98: Haussmannian apartment buildings (5cm insulation, single glazing) • CD_HLM_98: renovated social housing apartment buildings (5 cm insulation, single glazing)
1999–2003	IH_03: Modern house, double-glazing, 10 cm of insulation	• CD_BBC: Low-energy buildings (10 cm insulation, double glazing)

2.3.3 Evaluation of degree-hour of discomfort for 2003

Using dynamic thermal simulation and climatic data of 2003 based on measurements carried out in Montreuil (Paris suburbs), the degree-hours of discomfort for all archetypes were estimated over the summer of 2003. In this first version, the same climatic data were used to represent the whole metropolitan territory of France (i.e., excluding overseas territories) as the heat wave impact was comparable in all metropolitan regions, except for housing located at high altitude but the number of which is low, and which were neglected in this first study.

In 2003, very few dwellings in France were air-conditioned, so the simulation did not consider cooling. Opening windows was accounted for, considering a medium air flow rate of 2 ach (air change per hour). This value will be higher if windows are opened on two different facades and lower if people do not open windows.

Results as degree hours are presented in Table 3 below.

Concerning the collective dwellings, the degree hours have been averaged to account for the distinct thermal zones defined in the archetypes (according to storeys and orientation):

- BBC: average of 11 zones weighted on corresponding areas,
- Haussmannian: average over the 6 floors
- Social housing building: weighted average over the different floors and orientations

Finally, the corresponding total degree-hours of discomfort time area over the 2003 heat wave is estimated as follows:

$$\mathrm{DH.A}_{2003} = \sum_{\text{Building Stock}_{2003}} \mathrm{DH}_{2003} \times \mathrm{Area}_{2003} = 3.05 \times 10^{12}\ \mathrm{DH.m}^2$$

2.3.4 Determination of the characterisation factor

This allowed a ratio r of DALY / DH × area to be identified. The overheating DH can be obtained using thermal simulation for any building project and climate. The impacts on human health expressed in DALYs for this building can be evaluated by multiplying *r* with DH and the building area (net area is considered), assuming a proportionality in this first estimation. This corresponds to an LCA characterisation factor for overheating, $\mathrm{CF}_{\text{overheating}}$ associated with the DH.A elementary flow:

$$\mathrm{CF}_{\text{overheating}} = \frac{\mathrm{DALYs}_{2003}}{\mathrm{DH.A}_{2003}} = \frac{41\ 056}{3.05 \times 10^{12}} = 1.35 \times 10^{-8} \mathrm{DALY}/\left(\mathrm{m}^2\ \mathrm{Kh}\right)$$

Table 3 Results of the dynamic thermal simulations

	Degree-hour (K.h)	Net living area of 2003 residential building stock (millions of m^2)	DH × Area (K.h.m^2)
IH_75	1707	840	1.43 10^{12}
IH_98	1408	569	0.80 10^{12}
IH_03	723	723	0.05 10^{12}
CD_H_75	1069	218	0.23 10^{12}
CD_HLM_75	1631	218	0.36 10^{12}
CD_H_98	374	100	0.04 10^{12}
CD_HLM_98	1013	100	0.10 10^{12}
CD_BBC	571	58	0.03 10^{12}

To evaluate the potential damage to health impact related to climate change, prospective climatic data must be used in the thermal simulation to calculate DH corresponding to future climatic conditions. Keeping the same characterisation factor in a future context may be questioned, e.g., depending on the possible ageing of the population.

2.4 Description of the studied building and renovation project

The methodology described above was tested on a social housing building near Paris, including 52 apartments four floors above an unheated ground floor (Fig. 4). This type of building is relatively common in the French building stock, and it is used here as an example of the proposed method, which could be applied to any building. The net floor area is 4375 m^2. Built in 1969, the facades, roof, and floors were made of 20 cm concrete. A renovation project is studied, including thermal insulation on the facades and ceiling and replacing single-glazed windows with low-emissivity double-glazing. The wall insulation thickness is varied to identify a possible optimum: a low thickness induces impacts related to a high heating load and a high overheating, whereas a high thickness induces a high impact for fabricating the insulation material. The facade insulation material is rock wool. The insulation thickness on the roof is limited to 5 cm due to other constraints (rain management at a reasonable cost), and polyurethane was chosen to reduce heat losses.

The considered lifespan of the building after renovation is 80 years, and the number of inhabitants is 175. The building is heated by a district heating system (50% gas and 50% wood fuel as an energy source), and the thermostat set point is 21 °C from November to April. Each inhabitant consumes 100 L of cold water and 40 L of hot water daily. The air renewal rate is 0.36 ach (air change per hour) from mechanical ventilation and 0.14 ach from infiltration. In case of overheating, windows are opened if the indoor temperature is over 24 °C and if it is colder outdoors than indoors. Because some windows in a dwelling are on opposite facades (e.g., south-oriented living room and north-oriented bedrooms), a 10 ach air renewal flow rate is considered when windows are opened, following measurements results of Dupin et al. (2014). Solar protection is considered, assuming an average of 80% of solar gains reduction all day in summer, corresponding to closed white external shutters.

Thermal simulation was run using the prospective data corresponding to Paris in a distant future (2080–2100), considering an extreme heat wave. This allowed to evaluate heating loads and overheating degree-hours for each insulation thickness from 0 to 100 cm. An alternative with air conditioning is compared with and without insulation (15 cm rock wool), with and without a photovoltaic (PV) system (79 m^2).

The building is modelled considering several thermal zones, i.e., spaces assumed to be at the same temperatures. For instance, all south-oriented rooms on the same floor are grouped in the same zone. The ground floor of the building is used for non-residential activities; it is not heated. The top floor is divided into four zones, corresponding to orientation (North, South, East, and West). The three other floors are divided into four zones corresponding to the same four orientations. The reason is that the top floor is situated under the roof, with higher heat losses in winter and higher solar gains in summer (when the sun is high in the sky). Therefore, separating the top floor from the other floors is more accurate.

3 Results

As mentioned, thermal simulation (COMFIE tool) was performed using the typical meteorological year corresponding to the Greater Paris Area, the distant future (2080–2099), and the extreme heat wave. The overheating degree hours over the summer period were counted for each thermal zone, and an average value for the whole building was derived, each zone indicator being weighted by the corresponding zone area. Figure 5 shows the resulting average degree hours as a function of the insulation thickness.

Fig. 4 Case study building before (left) and after renovation (right)

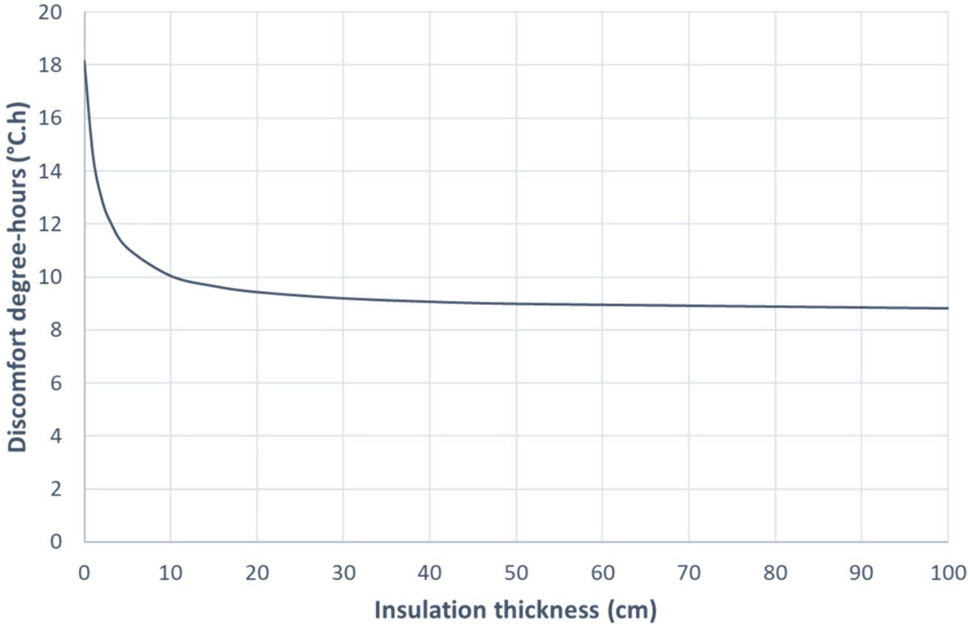


Fig. 5 Average degree-hours indicator in terms of the wall insulation thickness (COMFIE results)

According to these results, the first centimetres of insulation are very efficient at decreasing overheating, but after 20 cm, the effect of increasing the insulation thickness becomes much lower.

In the simplified model presented above, the DALYs corresponding to overheating are proportional to the DH indicator; the asymptotic variation in terms of the insulation thickness is similar.

On the other hand, the DALYs corresponding to the fabrication of insulation material are proportional to the volume and, therefore, to the thickness of insulation.

Another consequence of varying the insulation thickness is related to the heating needs, which also vary asymptotically in terms of insulation thickness (Fig. 6). The impact on human health of 1 kWh of heat provided by the district heating, derived from ecoinvent v3.4 data, is 3.15 10^{-7}DALY/kWh. The impacts of the heating system (connection to the district heating inside the building) are low. They are considered to have a negligible influence on the impact variation with the insulation thickness.

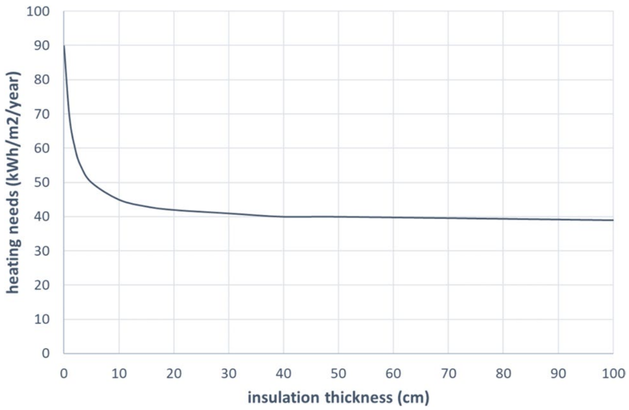


Fig. 6 Heating needs in terms of the insulation thickness (COMFIE results)

Regarding the three alternatives with air conditioning (without insulation, with 15 cm insulation, and with both insulation and PV), the annual cooling load resulting from the thermal simulation is 14 kWh/m^2 net living area without insulation and 6 kWh/m^2 net living area with 15 cm insulation. A seasonal energy efficiency ratio of 3 is assumed for the cooling system. A prospective hourly marginal electricity mix is used based on Roux et al. (2016) and Frapin et al. (2021), leading to an average of 1.36 10^{-6} DALY/kWh of electricity used for cooling. The maximum cooling load used to size the cooling system is 244 kW without insulation and 154 kW with 15 cm insulation. Assuming a 20-year lifespan for this system, this leads to 1.1 10^{-6} resp. 6.9 10^{-7} DALY/m^2 net living area/year without resp. with insulation. This study compares adaptation solutions based on a damage indicator integrating overheating and other LCA contributions; all contributions are expressed in DALY/m^2 net living area/year.

Impacts related to the photovoltaic system are evaluated according to the area of the modules, considering a 20-year lifespan, which leads to 5 10^{-7} DALY/m^2 net living area/year. PV electricity production is around 9000 kWh annually, slightly higher than cooling electricity consumption.

Impacts related to insulation fabrication and end-of-life depend on thickness. For instance, 12.4 tons of rock wool in the walls and 8.5 tons of polyurethane in the roof are used for a 15 cm thickness. The DALY indicator for fabrication and end-of-life processes is given in Table 4 (ecoinvent 3.4 database).

Table 4 DALYs corresponding to fabrication and end of life of 1 kg insulation material

Material	Fabrication	End of life
Rockwool	$3.10\ 10^{-6}$	$1.16\ 10^{-8}$ (landfill)
Polyurethane	$8.34\ 10^{-6}$	$2.74\ 10^{-6}$ (incineration)

Figure 7 shows the total impact in DALY/m2 net living area/year, indicating the different contributions.

According to the results of this first simplified method, the contribution of overheating is significant and can reach nearly half of the total damage indicator DALY. Without any cooling system, Fig. 7 shows an optimal insulation thickness of around 40 cm. Still, the difference is tiny at 15 cm, which could correspond to a reasonable compromise between performance and cost. Adding only a cooling system without renovating the envelope (0 insulation thickness, noted 0 + cooling in Fig. 7) leads to a high total impact due to heating and cooling loads. Adding a cooling system and 15 cm insulation reduces the total impact, as well as adding a PV system.

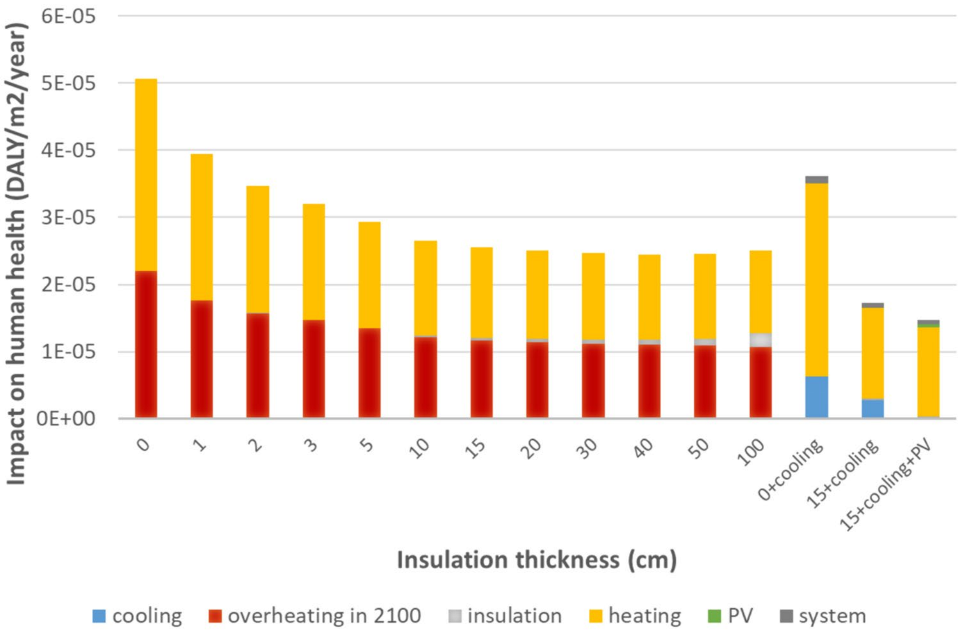
4 Discussion

Endpoint indicators, particularly regarding human health impacts, are highly uncertain. However, it may be argued that an uncertain indicator is preferable to no indicator. Improving the reliability of such indicators remains, of course, an open research question. The method proposed above adds uncertainty regarding how indoor overheating contributes to damage to human health, but integrating this aspect in the design of buildings is relevant. The order of magnitude obtained in this study is significant in terms of other contributions. This method is the first step in allowing the study of adaptation measures that contribute to mitigation.

The DH indicator has the advantage of integrating both the duration and intensity of overheating periods and considering the phenomenon of adaptive comfort. One assumption behind this indicator is that, e.g., a 2 °C temperature exceedance during 1 h induces the same damage to human health as a 1 °C exceedance during 2 h. The risk is related to increased body temperature, which does not vary instantaneously with indoor air temperature. Therefore, the health consequences depend on indoor temperature and the duration of the overheating period. This could be studied in more detail using thermal models of human bodies. The model could be refined by studying excess deaths each day of the year, including possible overheating in mid-season, instead of the total number during summer. Further collaboration with medical researchers is planned to study possible improvements to more accurately evaluate impacts on occupants' health.

The method's reliability could be improved by increasing the sample of data used to derive the damage indicator from overheating degree days. Only French data for the year 2003 were taken into account. New data exist for more recent years, which could be a valuable basis to know if the damage was reduced because appropriate actions were taken following feedback from past years. The influence of occupants' behaviour on overheating is very strong, so proper models could be helpful to account for this aspect (Schalbart et al. 2021). The presented case study corresponds to dwellings,

Fig. 7 Impacts on human health in terms of insulation thickness



including windows on two opposite facades, which allow high airflow. This possibility of free-cooling would be more limited in other configurations. Similar studies could also be performed in other countries with different humidity conditions, different building stocks, population composition and behaviours. Applying this interim characterisation factor to other areas of the world should be done with high caution. A differentiation between heat discomfort and heat stress thresholds could also be introduced to better evaluate human health damage due to severe heat waves.

The existing building stock could be modelled more precisely, considering various archetypes, including older adults' homes, though, in France, these buildings are now equipped with air conditioning.

Only premature deaths were taken into account in this study. Overheating may also cause health problems: respiratory, blood pressure, core temperature, blood glucose, mental health and cognition, heat-health symptoms, physical functioning, and influenza transmission were reported by Tham et al. (2020). Interaction may occur between temperature and humidity (Givoni 1992), so the risk of overheating may be higher when humidity increases.

Moreover, based on data available in the INSERM report (Hémon and Jougla 2004) and INSEE statistics (INSEE 2020), only the increased mortality risk for people over 50 years old was accounted for. Health effects on younger people should also be considered, particularly if the method is extended to non-lethal diseases. This will further be discussed with medical researchers.

Going from this interim characterisation factor to a more reliable model implies deriving uncertainty information. Several climatic models and emission scenarios could be used to evaluate uncertainty on future climatic data (intensity and duration of heat waves) and further uncertainty on degree-hours of discomfort. Near or distant future evaluation can also be used to look at median and extreme heat waves. Further, the occupancy ratio can also be varied, as can occupant sensitivity to heat, occupant behaviour regarding windows opening, shadings, hours of presence, and internal and metabolic heat gains. This critical step is highly data intensive but would be necessary to perform sensitivity analysis and precisely evaluate the improvement priority of the current modelling.

The damage is evaluated as a DALY indicator. DALYs resulting from LCA correspond to damages at any location, whereas overheating-related DALYs correspond precisely to the occupants of a studied building. It may be questionable whether the different contributions can be added. However, several effects with highly different spatial and temporal scales have already been added to the present standard LCA practice (e.g., climate change and toxicity).

Damage to human health due to overheating is influenced by building design, which is the focus of this study. However, overheating could also be attributed to climate change and, thus, to GHG emissions. This first interim modelling for building might be a way to complete the evaluation of the damage linked to climate change, as only the increase in the risk of disease (malnutrition, malaria, and diarrhoea) is currently included in The ReCiPe2016 method. Moving toward the inclusion of overheating implies a rigorous treatment of potential double counting when considering building LCA.

5 Conclusions and perspectives

Both mitigation and adaptation to climate change should be targeted when designing buildings. Standard practice consists of performing separate studies in parallel, hoping the corresponding solutions do not contradict. Unfortunately, this is not always the case: for instance, active cooling is an efficient adaptation measure but induces environmental impacts. Proposing a global evaluation accounting for all life cycle impacts, including the effects of indoor overheating, helps to find design solutions depending on climatic conditions and building uses.

The first simplified approach presented in this study shows that overheating contributes significantly and can reach nearly half of the total damage indicator DALY. Therefore, refining this approach would be useful, as would updating it using more recent data. This opens several research perspectives, particularly taking advantage of data over longer periods and at a broader geographic scale, including a larger variety of buildings and occupants' behaviours, as well as various health effects also linked to humidity.

Author contributions Conceptualization: Bruno Peuportier, Patrick Schalbart; Methodology: Robin Monnier, Bruno Peuportier, Patrick Schalbart; Formal analysis and investigation: Robin Monnier; Writing - original draft preparation: Robin Monnier, Bruno Peuportier, Charlotte Roux, Patrick Schalbart; Writing - review and editing: Bruno Peuportier, Charlotte Roux, Patrick Schalbart; Funding acquisition: Bruno Peuportier; Supervision: Bruno Peuportier.

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Data availability The authors declare that the main data supporting the findings of this study are available within the paper. Details on very specific thermal dynamic simulations or LCA hypotheses are available on request. Considering thermal dynamic simulation, the commercial software Pléiades® was used, but open-source tools such as EnergyPlus (https://energyplus.net/) could also be used.

Declarations

Competing interests The authors declare no competing interests.

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