



HAL
open science

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

Robin Monnier, Patrick Schalbart, Charlotte Roux, Bruno Peuportier

► To cite this version:

Robin Monnier, Patrick Schalbart, Charlotte Roux, Bruno Peuportier. Integrating effects of overheating on human health into buildings' life cycle assessment. *International Journal of Life Cycle Assessment*, 2024, 29 (11), pp.2137-2150. 10.1007/s11367-024-02353-3 . hal-04814485

HAL Id: hal-04814485

<https://hal.science/hal-04814485v1>

Submitted on 10 Dec 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

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

Robin Monnier^a, Patrick Schalbart^a, Charlotte Roux^a and Bruno Peuportier^a

^aMines Paris, Center for Energy Efficiency of Systems, 60 Boulevard Saint-Michel, 75006 Paris, France

ORCID

Patrick Schalbart: <https://orcid.org/0000-0002-3021-9076>

Charlotte Roux: <https://orcid.org/0000-0002-9176-5038>

Bruno Peuportier: <https://orcid.org/0000-0002-1085-3280>

*Corresponding author: charlotte.roux@minesparis.psl.eu

Telephone: +33140519151

14 **Abstract**

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

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

28 Results: The proposed overheating model not only allows to derive a characterisation factor for overheating to be
29 used in building LCA but also provides practical insights. The first estimation of the characterisation factor is
30 $1.35E-8 \text{ DALY} \cdot \text{DH}^{-1} \cdot \text{m}^{-2}$. The method was tested in a case study corresponding to a social housing apartment
31 building in France built in 1969 without insulation. The thickness of insulation implemented in the renovation
32 works was varied. For this specific case study, the contribution of overheating is significant, ranging from $1.1E-$
33 $5 \text{ DALY} \cdot \text{m}^{-2} \cdot \text{y}^{-1}$ to $2.2E-5 \text{ DALY} \cdot \text{m}^{-2} \cdot \text{y}^{-1}$, comparable to the contribution of heating. DTS and LCA results found
34 an optimal thickness, minimising the human health indicator in DALYs. This underscores the potential of active
35 cooling to reduce human health impacts, especially if it consumes electricity produced by a photovoltaic system
36 integrated in the building.

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

41 Keywords: Building, overheating, mitigation, adaptation, DALY

42 **1 INTRODUCTION**

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

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

51 Environmental impacts are assessed using LCA (Ortiz et al. 2009; Cabeza et al. 2014; Anand and Amor 2017).
52 Active solutions (air conditioning) induce environmental impacts due to the fabrication and energy use of cooling
53 systems. Passive solutions include solar protection, night ventilation, increasing thermal insulation (Peuportier
54 2004; Porritt et al. 2012), and thermal mass (Peuportier and Thiers 2009). Such solutions improve thermal
55 comfort: opening windows at night cools the walls and slabs during hot summer and mid-season, solar protection
56 and high insulation reduce heat transfer, and thermal mass reduces temperature fluctuation, limiting
57 overheating. On the other hand, the fabrication of shading systems, insulation, and masonry induces
58 environmental impacts.

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

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

- 73 - the microclimate with actions on trees, greening of facades or roofs (Gromke et al. 2015), cooling road
74 surfaces in summer to store heat in the ground and use it in winter is mentioned (Albers et al. 2015), use
75 of reflective roofs and road surfaces (Akbari and Matthews 2012; Synnefa et al. 2012),
- 76 - the envelope with solar protection, insulation, coverings (Akbari and Matthews 2012), thermal mass
77 (Kendrick et al. 2012; van Hooff et al. 2014),
- 78 - ventilation with nocturnal over-ventilation (Dupin et al. 2014), ground heat exchangers,
- 79 - systems with air fans, cooling, air conditioning, evaporative cooling (Smith et al. 2011; Maillard et al.
80 2014; Montazeri et al. 2015; Pomianowski et al. 2015),
- 81 - or the occupants with windows opening, managing solar protection, or limiting internal heat gains.

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

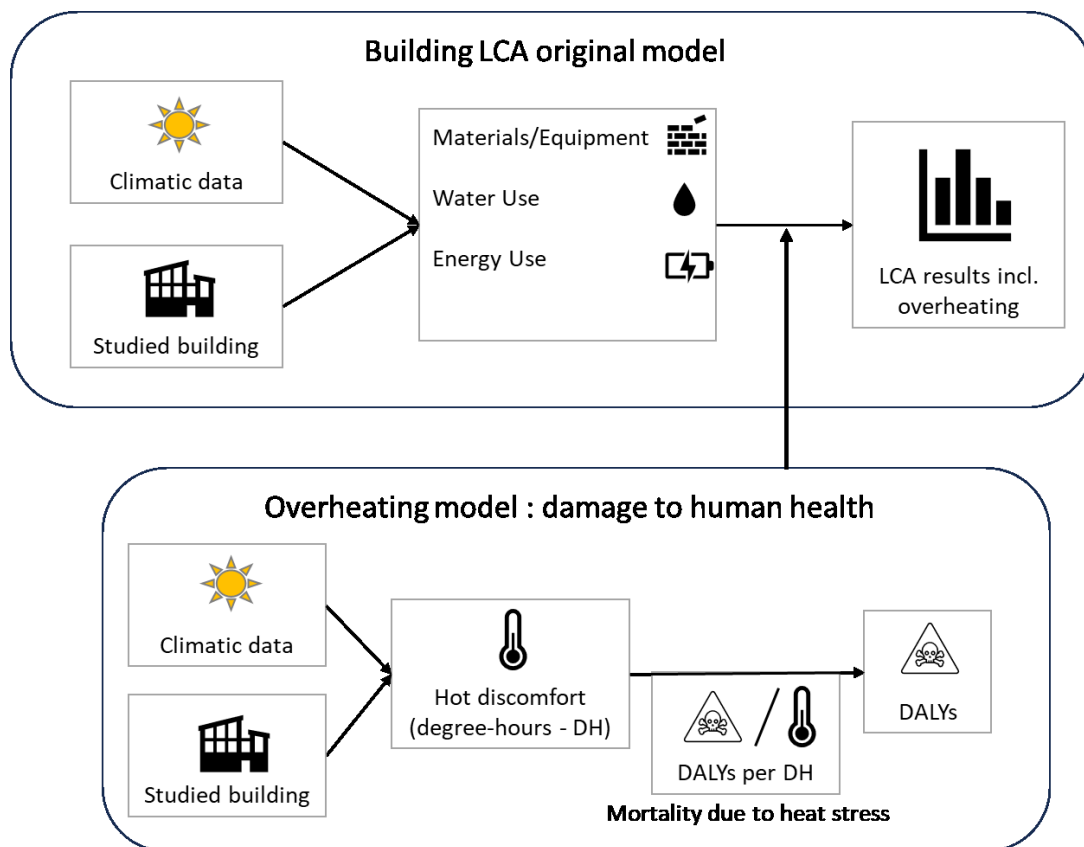
89 This article proposes a first simplified evaluation method, aiming at estimating an order of magnitude of the effect
90 of overheating on human health and comparing it with other LCA contributors considering the same damage
91 indicator. If the effect of overheating is significant, refining this method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

97

98 **2 MATERIAL AND METHODS**

99 The proposed method complements a usual Building LCA by integrating the impacts of overheating on human
100 health. Overheating is evaluated using climatic data as input for dynamic thermal simulation, and an elementary
101 flow is derived, complementing the usual life cycle inventory. Impact assessment is then performed using an
102 interim characterisation factor based on mortality data from 2003 in France. The methodology can be applied in
103 other contexts considering various climates, construction techniques and occupants' behaviour. Materials, water,
104 and energy-related impacts are evaluated considering the damage to human health indicator defined in the ReCiPe
105 2016 impact assessment method (Huijbregts et al., 2017). The overall framework is summarised in Figure 1 below.
106 The upper part corresponds to a usual Building LCA. The proposed complement is illustrated in the lower part.
107 The following paragraphs present the scope, inventory, and impact assessment steps; the last is a case study
108 description.

109



110

111 **Figure 1: Overall framework**

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 Jouglu 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; 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 the discussion chapter.

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, I. 1990). STD COMFIE was chosen because it is linked to an

140 LCA tool, and the thermal model was studied in several validation studies, e.g. (Brun et al. 2009; Munaretto et al.
141 2017).

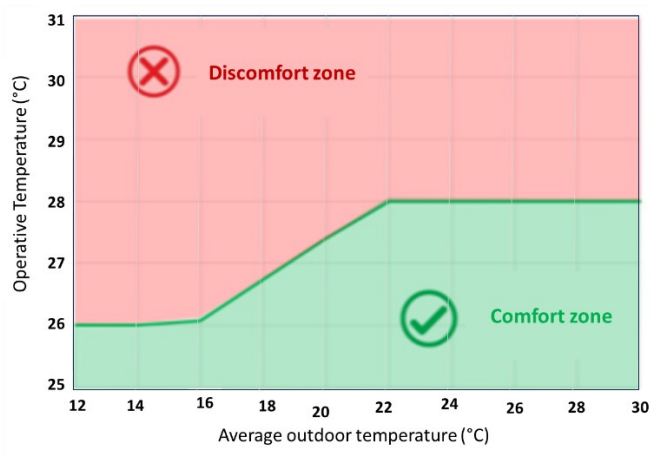
142 Because buildings are long-lasting systems, numerous studies have addressed the impact of climate change in
143 terms of heating and air conditioning needs, for example, in Switzerland (Frank 2005), in Great Britain (Hacker et
144 al. 2008; Collins et al. 2010; Kolokotroni et al. 2012; Williams et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

147 **2.2 Inventory**

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

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

158 The temperature exceedance is related to a threshold. This threshold could be a fixed temperature, for example,
159 28°C (Porritt et al. 2012), or vary according to an adaptive comfort approach (van Hooff et al. 2014). To consider
160 people's habituation of heat, we have chosen an adaptive comfort approach based on the standard EN 16798-1
161 (CEN 2019b). By this standard, the hot discomfort threshold temperature considered is calculated at each time step
162 (one hour in this study) based on the daily rolling average outdoor temperature (see Figure 2).



163

164 **Figure 2: threshold discomfort temperature in terms of the average outdoor temperature of the previous day**

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

172 The calculation of this DH indicator consists of summing the hourly difference between the zone's operational
 173 temperature and the discomfort threshold over the occupancy period during a summer period. The operational
 174 temperature integrates air and wall temperatures to account for convective and radiative heat transfer, which
 175 influences the comfort sensation of occupants and possible health risks.

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

180 Studying the adaptation of buildings to climate change requires the availability of appropriate climate data (Guan
 181 2009). Dynamic thermal simulation tools generally use data over a year at hourly intervals: temperature, solar
 182 radiation, wind, humidity, etc. It is, therefore, not enough to only know the annual average temperature increase.
 183 Previous studies used climate projections (Kershaw et al. 2011; Jenkins et al. 2015). A collaboration with the
 184 French meteorological research centre allowed prospective climate data to be developed for French climates,

185 particularly the Greater Paris Area considered in this study. The highest greenhouse gas emissions scenario,
186 RCP8.5 (Representative Concentration Pathway, radiative forcing 8.5 W/m²), was considered. Because dynamic
187 thermal simulation models need hourly meteorological data and to take into account the urban signal, we used very
188 high-resolution climate simulations (2.5 km) carried out with the AROME climate model (Daniel 2017; Fumière
189 et al. 2020; Caillaud et al. 2021) combined with the TEB (Town Energy Balance) urban diagram (Masson 2000).
190 AROME simulations are also produced by dynamic downscaling (Seity et al. 2011; Voltaire et al. 2013). Two
191 time periods were simulated, corresponding to a near future (2041-2050, 10 years) and a distant future (2080-2099,
192 20 years).

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

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

- 203 • a median heat wave which corresponds to the heat wave simulated by AROME whose duration (in
204 number of days) and severity are the closest to the median of the duration and severity of the events;
- 205 • an extreme heat wave corresponding to the closest heat wave to quantile 95 of the set of events.

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

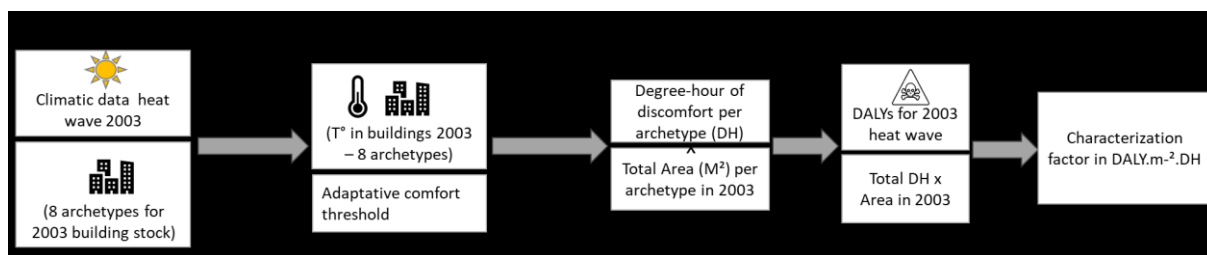
209 Choosing between a near or distant future and a median or extreme heat wave could be left to the user's decision,
210 depending on the study objectives. It could also be used to evaluate uncertainty on the degree-hour evaluation due
211 to temporal (near to distant future) and intrinsic (median, extreme) variability of the heat waves' intensity and

212 duration. As the goal is here to evaluate the significance of overheating compared to other contributions to damage
 213 to human health, a worst-case scenario with extreme heat waves and a distant future was selected in the case study.
 214 The damage caused by overheating to human health depends on the number of occupants in the studied building.
 215 At the design stage, this parameter is unknown. For instance, an apartment can be designed for a four-person
 216 family, but after some time, the children leave home. It is, therefore, current practice in building design to consider
 217 a typical number of occupants according to the net living area, e.g., 25 m² average area per person. The net living
 218 area is the floor area, excluding walls and spaces like cellars, parking places and attics. A linear model is considered
 219 in this first simplified approach: the damage is proportional to the net living area, noted A. The damage is assumed
 220 to be proportional to both DH and A, and the elementary flow considered is DH.A, expressed in K.h.m².

221 2.3 Interim characterisation factor and impact assessment

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

226 Using detailed mortality data from the 2003 heat wave in France associated with a simple model of the French
 227 2003 building stocks, an interim characterisation factor for damage to human health due to overheating is derived,
 228 as explained in Figure 3 below.



229
 230 **Figure 3: interim characterization factor development**

231 First, the number of DALYs attributed to the 2003 heat wave was evaluated. Then, a simple model of the 2003
 232 building stock was built based on eight archetypes with corresponding areas A. Finally, thanks to dynamic thermal
 233 simulation, the degree-hour of discomfort (DH) per archetype was determined based on the climatic data from
 234 2003. This allowed to express a ratio of DALY/DH.A, which can then be used as a characterisation factor in
 235 building LCA.

236 Evaluation of DALYs for the 2003 heat wave

237 The National Institute of Statistics in France evaluated the excess deaths from the 2003 heat wave to 15300 deaths
 238 (INSEE 2020) from 1 to 24 August. According to mortality monitoring, the fatalities returned to normal after the
 239 heat wave until the end of 2003 (Hémon and Jouglà 2004). The expected number of deaths is evaluated based on
 240 four years: from 1999 to 2002. In past years, an average of 31,700 deaths were reported over the same period,
 241 against 47,000 in 2003. No significant excess of deaths was reported during the rest of the 2003 summer. The
 242 number of excess deaths is provided for different age intervals (see Table 1).

243 In this study, we use a “reference age” of 78 to evaluate the number of years of life lost. This figure was obtained
 244 by calculating the average age at death in 2003, as life expectancy depends on the birth year and was lower in the
 245 20th century than today. Using a life expectancy could lead to underestimating the number of years of life lost.

246 Following this procedure, an excess death at 77 years old would lead to 1 year of life loss, and so to 1 DALY as
 247 non-lethal diseases could not be included in this first study due to lack of data: this topic constitutes a research
 248 perspective. For instance, if during a heat wave occurring year y , the number of excess deaths is n in the age
 249 interval between 65 and 74 and the considered reference age is 78 years, the corresponding number of DALYs is
 250 evaluated as $n \cdot (78 - (65 + 74) / 2)$. Possible confounding factors and interaction between overheating and other health
 251 problems are not considered in this first simplified method (see the discussion §). A total DALY indicator is
 252 derived by adding the contribution of the different age intervals below the reference age. From the excess deaths
 253 evaluated by the French National Statistical Institute (INSEE 2020) for each age range, the total number of DALYs
 254 (41056) due to the 2003 heat wave was derived as detailed in Table 1 below and based on the following equation
 255 for each age range:

$$DALYs = (ReferenceAge - AverageAgeAtDeath) \times ExcessDeath$$

258 **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	<u>41056</u>

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

260

261 **2003 Building stock model**

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

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

271 **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	<ul style="list-style-type: none"> • CD_H_75: Haussmannian apartment buildings (not insulated, single glazing) • CD_HLM_75: non-insulated social housing apartment buildings (not insulated, single glazing) • CD_H_98: Haussmannian apartment buildings (5cm insulation, single glazing)
1975 – 1998	IH_98: 1950 house renovated, single glazing, 5cm of insulation	<ul style="list-style-type: none"> • CD_HLM_98: renovated social housing apartment buildings (5cm insulation, single glazing)
1999 – 2003	IH_03: Modern house, Double-glazing, 10cm of insulation	<ul style="list-style-type: none"> • CD_BBC: Low-energy buildings (10cm insulation, double glazing)

272

273 **Evaluation of degree-hour of discomfort for 2003**

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

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

282 Results as degree hours are presented in Table 3 below.

283 **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 x 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

284
 285 Concerning the collective dwellings, the degree hours have been averaged to account for the distinct thermal zones
 286 defined in the archetypes (according to storeys and orientation):

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

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

$$292 \quad DH.A_{2003} = \sum_{Building\ Stock_{2003}} DH_{2003} \times Area_{2003} = 3.05 \times 10^{12} DH.m^2$$

293 **Determination of the characterisation factor**

294 This allowed a ratio r of DALY / DH×area to be identified. The overheating DH can be obtained using thermal
 295 simulation for any building project and climate. The impacts on human health expressed in DALYs for this
 296 building can be evaluated by multiplying r with DH and the building area (net area is considered), assuming a
 297 proportionality in this first estimation. This corresponds to an LCA characterisation factor for overheating,
 298 $CF_{overheating}$ associated with the DH.A elementary flow:

299
$$CF_{overheating} = \frac{DALY_{S_{2003}}}{DH \cdot A_{2003}} = \frac{41\ 056}{3.05 \times 10^{12}} = 1.35 \times 10^{-8} DALY/(m^2 \cdot Kh)$$

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

304 **2.4 Description of the studied building and renovation project**

305 The methodology described above was tested on a social housing building near Paris, including 52 apartments
306 four floors above an unheated ground floor (Figure 4). This type of building is relatively common in the French
307 building stock, and it is used here as an example of the proposed method, which could be applied to any building.
308 The net floor area is 4,375 m². Built in 1969, the facades, roof, and floors were made of 20 cm concrete. A
309 renovation project is studied, including thermal insulation on the facades and ceiling and replacing single-glazed
310 windows with low-emissivity double-glazing. The wall insulation thickness is varied to identify a possible
311 optimum: a low thickness induces impacts related to a high heating load and a high overheating, whereas a high
312 thickness induces a high impact for fabricating the insulation material. The facade insulation material is rock wool.
313 The insulation thickness on the roof is limited to 5 cm due to other constraints (rain management at a reasonable
314 cost), and polyurethane was chosen to reduce heat losses.



316 **Figure 4: Case study building before (left) and after renovation (right)**

317 The considered lifespan of the building after renovation is 80 years, and the number of inhabitants is 175. The
318 building is heated by a district heating system (50 % gas and 50 % wood fuel as an energy source), and the
319 thermostat set point is 21°C from November to April. Each inhabitant consumes 100 L of cold water and 40 L of
320 hot water daily. The air renewal rate is 0.36 ach (air change per hour) from mechanical ventilation and 0.14 ach
321 from infiltration. In case of overheating, windows are opened if the indoor temperature is over 24°C and if it is

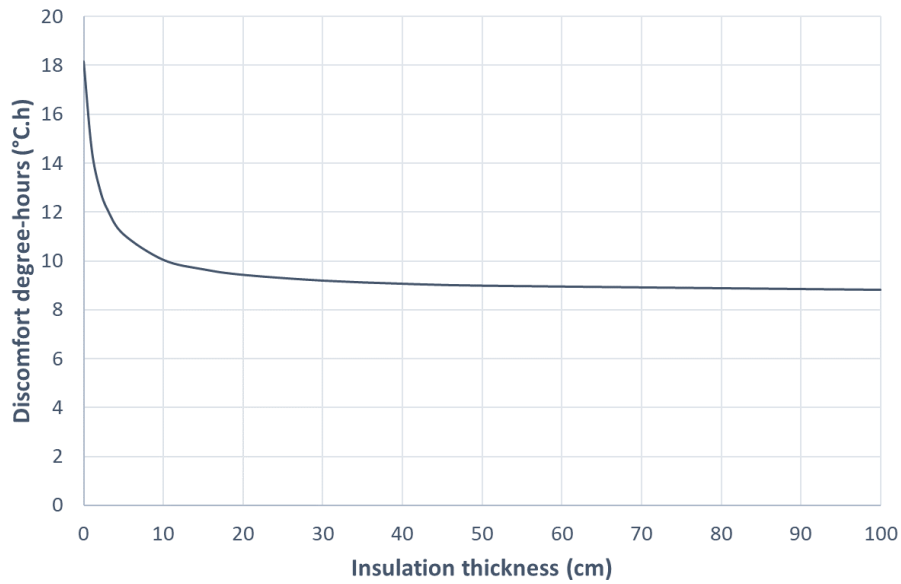
322 colder outdoors than indoors. Because some windows in a dwelling are on opposite facades (e.g., south-oriented
323 living room and north-oriented bedrooms), a 10 ach air renewal flow rate is considered when windows are opened,
324 following measurements results of (Dupin et al. 2014). Solar protection is considered, assuming an average of
325 80 % of solar gains reduction all day in summer, corresponding to closed white external shutters.

326 Thermal simulation was run using the prospective data corresponding to Paris in a distant future (2080-2100),
327 considering an extreme heat wave. This allowed to evaluate heating loads and overheating degree-hours for each
328 insulation thickness from 0 to 100 cm. An alternative with air conditioning is compared with and without insulation
329 (15 cm rock wool), with without and without a photovoltaic (PV) system (79 m²).

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

337 **3 RESULTS**

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



343

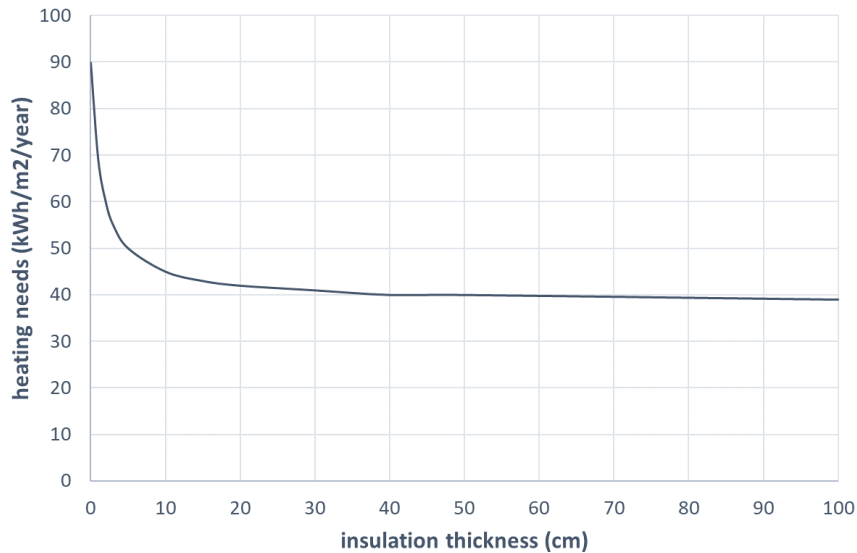
344 **Figure 5: Average Degree-hours indicator in terms of the wall insulation thickness (COMFIE results)**

345 According to these results, the first centimetres of insulation are very efficient at decreasing overheating, but after
 346 20 cm, the effect of increasing the insulation thickness becomes much lower.

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

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

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



356

357 **Figure 6: Heating needs in terms of the insulation thickness (COMFIE results)**

358 Regarding the three alternatives with air conditioning (without insulation, with 15 cm insulation, and with both
 359 insulation and PV), the annual cooling load resulting from the thermal simulation is 14 kWh/m² net living area
 360 without insulation and 6 kWh/m² net living area with 15 cm insulation. A seasonal energy efficiency ratio of 3 is
 361 assumed for the cooling system. A prospective hourly marginal electricity mix is used based on (Roux et al. 2016;
 362 Frapin et al. 2021), leading to an average of 1.36 10⁻⁶ DALY/kWh of electricity used for cooling. The maximum
 363 cooling load used to size the cooling system is 244 kW without insulation and 154 kW with 15 cm insulation.
 364 Assuming a 20-year lifespan for this system, this leads to 1.1 10⁻⁶ resp. 6.9 10⁻⁷ DALY/m² net living area/year
 365 without resp. with insulation. This study compares adaptation solutions based on a damage indicator integrating
 366 overheating and other LCA contributions; all contributions are expressed in DALY/m² net living area/year.

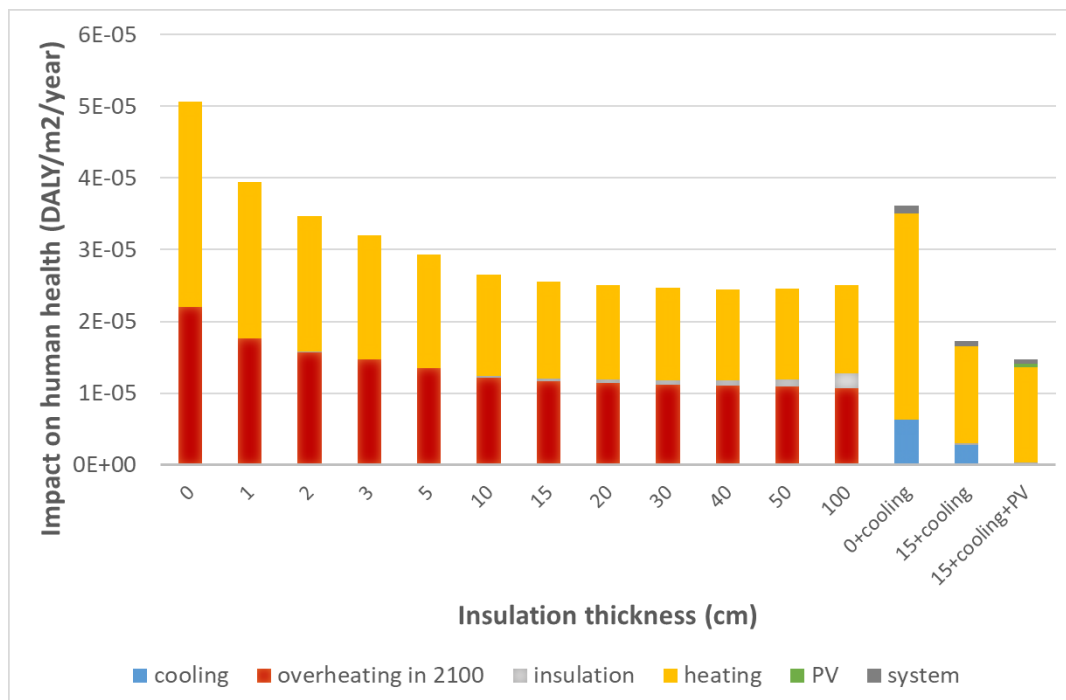
367 Impacts related to the photovoltaic system are evaluated according to the area of the modules, considering a 20-
 368 year lifespan, which leads to 5 10⁻⁷ DALY/m² net living area/year. PV electricity production is around 9,000 kWh
 369 annually, slightly higher than cooling electricity consumption.

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

373 **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)

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



375

376 **Figure 7: Impacts on human health in terms of insulation thickness**

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

383 **4 DISCUSSION**

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

390 The DH indicator has the advantage of integrating both the duration and intensity of overheating periods and
391 considering the phenomenon of adaptive comfort. One assumption behind this indicator is that, e.g., a 2°C
392 temperature exceedance during one hour induces the same damage to human health as a 1°C exceedance during
393 2 hours. The risk is related to increased body temperature, which does not vary instantaneously with indoor air
394 temperature. Therefore, the health consequences depend on indoor temperature and the duration of the overheating
395 period. This could be studied in more detail using thermal models of human bodies. The model could be refined
396 by studying excess deaths each day of the year, including possible overheating in mid-season, instead of the total
397 number during summer. Further collaboration with medical researchers is planned to study possible improvements
398 to more accurately evaluate impacts on occupants' health.

399 The method's reliability could be improved by increasing the sample of data used to derive the damage indicator
400 from overheating degree days. Only French data for the year 2003 were taken into account. New data exist for
401 more recent years, which could be a valuable basis to know if the damage was reduced because appropriate actions
402 were taken following feedback from past years. The influence of occupants' behaviour on overheating is very
403 strong, so proper models could be helpful to account for this aspect (Schalbart et al. 2021). The presented case
404 study corresponds to dwellings, including windows on two opposite facades, which allow high airflow. This
405 possibility of free-cooling would be more limited in other configurations. Similar studies could also be performed
406 in other countries with different humidity conditions, different building stocks, population composition and
407 behaviours. Applying this interim characterisation factor to other areas of the world should be done with high
408 caution. A differentiation between heat discomfort and heat stress thresholds could also be introduced to better
409 evaluate human health damage due to severe heat waves.

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

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

417 Moreover, based on data available in the INSERM report (Hémon and Jouglu, 2004) and INSEE statistics (INSEE,
418 2020), only the increased mortality risk for people over 50 years old was accounted for. Health effects on younger

419 people should also be considered, particularly if the method is extended to non-lethal diseases. This will further
420 be discussed with medical researchers.

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

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

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

439 **5 CONCLUSIONS AND PERSPECTIVES**

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

445 The first simplified approach presented in this study shows that overheating contributes significantly and can reach
446 nearly half of the total damage indicator DALY. Therefore, refining this approach would be useful, as would

447 updating it using more recent data. This opens several research perspectives, particularly taking advantage of data
448 over longer periods and at a broader geographic scale, including a larger variety of buildings and occupants'
449 behaviours, as well as various health effects also linked to humidity.

450 **6 DECLARATIONS**

451 **6.1 Funding and Competing interests**

452 This study was performed with the financial support of the French Environment Agency (ADEME), and the chair
453 lab recherche environnement VINCI ParisTech. The authors have no relevant financial or non-financial interests
454 to disclose.

455 **6.2 Credit Author Statement**

456 Conceptualization: Bruno Peuportier, Patrick Schalbart; Methodology: Robin Monnier, Bruno Peuportier, Patrick
457 Schalbart; Formal analysis and investigation: Robin Monnier; Writing - original draft preparation: Robin Monnier,
458 Bruno Peuportier, Charlotte Roux, Patrick Schalbart; Writing - review and editing: Bruno Peuportier, Charlotte
459 Roux, Patrick Schalbart; Funding acquisition: Bruno Peuportier; Supervision: Bruno Peuportier

460 **6.3 Data availability**

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

465 **7 REFERENCES**

- 466 ADEME (2006) Key figures on buildings - 2006 Edition (in French)
- 467 Akbari H, Matthews HD (2012) Global cooling updates: Reflective roofs and pavements. *Energy Build* 55:2–6.
468 <https://doi.org/10.1016/j.enbuild.2012.02.055>
- 469 Albers RAW, Bosch PR, Blocken B, et al (2015) Overview of challenges and achievements in the climate
470 adaptation of cities and in the Climate Proof Cities program. *Build Environ* 83:1–10.
471 <https://doi.org/10.1016/j.buildenv.2014.09.006>
- 472 Anand CK, Amor B (2017) Recent developments, future challenges and new research directions in LCA of
473 buildings: A critical review. *Renew Sustain Energy Rev* 67:408–416.
474 <https://doi.org/10.1016/j.rser.2016.09.058>
- 475 Brown SJ (2020) Future changes in heatwave severity, duration and frequency due to climate change for the most
476 populous cities. *Weather Clim Extrem* 30:100278. <https://doi.org/10.1016/j.wace.2020.100278>
- 477 Brun A, Spitz C, Mora EW and L (2009) Behavioural comparison of some predictive tools used in a low-energy
478 building. 11th IBPSA Conf Glasg Scotl July 27-30

- 479 Bulle C, Margni M, Patouillard L, et al (2019) IMPACT World+: a globally regionalized life cycle impact
480 assessment method. *Int J Life Cycle Assess* 24:1653–1674. <https://doi.org/10.1007/s11367-019-01583-0>
- 481 Cabeza LF, Rincón L, Vilariño V, et al (2014) Life cycle assessment (LCA) and life cycle energy analysis (LCEA)
482 of buildings and the building sector: A review. *Renew Sustain Energy Rev* 29:394–416.
483 <https://doi.org/10.1016/j.rser.2013.08.037>
- 484 Caillaud C, Somot S, Alias A, et al (2021) Modelling Mediterranean heavy precipitation events at climate scale:
485 an object-oriented evaluation of the CNRM-AROME convection-permitting regional climate model.
486 *Clim Dyn* 56:1717–1752. <https://doi.org/10.1007/s00382-020-05558-y>
- 487 CEN (2019a) Standard EN 15804+A2 Sustainability of construction works - Environmental product declarations
488 - Core rules for the product category of construction products
- 489 CEN (2012) Standard EN 15978 Sustainability of construction works - Assessment of environmental performance
490 of buildings - Calculation method
- 491 CEN (2019b) Standard EN 16798-1 Energy performance of buildings - Ventilation for buildings - Part 1 : indoor
492 environmental input parameters for design and assessment of energy performance of buildings addressing
493 indoor air quality, thermal environment, lighting and acoustics - Module M1
- 494 CEREN (2006) Secteur résidentiel Suivi du parc et des consommations d'énergie. Évolution de 1982 à 2005
- 495 Collins L, Natarajan S, Levermore G (2010) Climate change and future energy consumption in UK housing stock.
496 *Build Serv Eng Res Technol* 31:75–90. <https://doi.org/10.1177/0143624409354972>
- 497 Daniel M (2017) Villes, climat urbain et climat régional sur la France : étude par une approche de modélisation
498 climatique couplée. Phdthesis, Université Paul Sabatier - Toulouse III
- 499 de Wilde P, Coley D (2012) The implications of a changing climate for buildings. *Build Environ* 55:1–7.
500 <https://doi.org/10.1016/j.buildenv.2012.03.014>
- 501 Dupin N, Peuportier B, Duer K, et al (2014) Evaluation of ventilative cooling in a single family house -
502 Characterization and modelling of natural ventilation. Sustainable building conference, Barcelona,
503 October 2014
- 504 Frank Th (2005) Climate change impacts on building heating and cooling energy demand in Switzerland. *Energy*
505 *Build* 37:1175–1185. <https://doi.org/10.1016/j.enbuild.2005.06.019>
- 506 Frapin M, Roux C, Assoumou E, Peuportier B (2021) Modelling long-term and short-term temporal variation and
507 uncertainty of electricity production in the life cycle assessment of buildings. *Appl Energy* 118141.
508 <https://doi.org/10.1016/j.apenergy.2021.118141>
- 509 Frischknecht R, Rebitzer G (2005) The ecoinvent database system: a comprehensive web-based LCA database. *J*
510 *Clean Prod* 13:1337–1343. <https://doi.org/10.1016/j.jclepro.2005.05.002>
- 511 Fumière Q, Déqué M, Nuissier O, et al (2020) Extreme rainfall in Mediterranean France during the fall: added
512 value of the CNRM-AROME Convection-Permitting Regional Climate Model. *Clim Dyn* 55:77–91.
513 <https://doi.org/10.1007/s00382-019-04898-8>
- 514 Givoni B (1992) Comfort, climate analysis and building design guidelines. *Energy Build* 18:11–23.
515 [https://doi.org/10.1016/0378-7788\(92\)90047-K](https://doi.org/10.1016/0378-7788(92)90047-K)
- 516 Gosling SN, Bryce EK, Dixon PG, et al (2014) A glossary for biometeorology. *Int J Biometeorol* 58:277–308.
517 <https://doi.org/10.1007/s00484-013-0729-9>
- 518 Gromke C, Blocken B, Janssen W, et al (2015) CFD analysis of transpirational cooling by vegetation: Case study
519 for specific meteorological conditions during a heat wave in Arnhem, Netherlands. *Build Environ* 83:11–
520 26. <https://doi.org/10.1016/j.buildenv.2014.04.022>

- 521 Guan L (2009) Preparation of future weather data to study the impact of climate change on buildings. *Build*
522 *Environ* 44:793–800. <https://doi.org/10.1016/j.buildenv.2008.05.021>
- 523 Gupta R, Gregg M (2012) Using UK climate change projections to adapt existing English homes for a warming
524 climate. *Build Environ* 55:20–42. <https://doi.org/10.1016/j.buildenv.2012.01.014>
- 525 Hacker JN, De Saulles TP, Minson AJ, Holmes MJ (2008) Embodied and operational carbon dioxide emissions
526 from housing: A case study on the effects of thermal mass and climate change. *Energy Build* 40:375–
527 384. <https://doi.org/10.1016/j.enbuild.2007.03.005>
- 528 Hall IJ, Prairie RR, Anderson HE, Boes EC (1978) Generation of a typical meteorological year. Sandia Labs.,
529 Albuquerque, NM (USA)
- 530 Hémon D, Jouglu E (2004) Surmortalité liée à la canicule d’août 2003. Rapp D’étape INSERM Paris
- 531 Huijbregts MAJ, Steinmann ZJN, Elshout PMF, et al (2017) ReCiPe2016: a harmonised life cycle impact
532 assessment method at midpoint and endpoint level. *Int J Life Cycle Assess* 22:138–147.
533 <https://doi.org/10.1007/s11367-016-1246-y>
- 534 Ibbetson A, Milojevic A, Mavrogianni A, et al (2021) Mortality benefit of building adaptations to protect care
535 home residents against heat risks in the context of uncertainty over loss of life expectancy from heat.
536 *Clim Risk Manag* 32:100307. <https://doi.org/10.1016/j.crm.2021.100307>
- 537 INSEE (2020) Plus de décès pendant l’épisode de Covid-19 du printemps 2020 qu’au cours de la canicule de 2003
- 538 Jenkins DP, Patidar S, Simpson SA (2015) Quantifying Change in Buildings in a Future Climate and Their Effect
539 on Energy Systems. *Buildings* 5:985–1002. <https://doi.org/10.3390/buildings5030985>
- 540 Jolliet O, Saadé-Sbeih M, Shaked S, et al (2015) *Environmental Life Cycle Assessment*, CRC Press. CRC Press
- 541 Kendrick C, Ogden R, Wang X, Baiche B (2012) Thermal mass in new build UK housing: A comparison of
542 structural systems in a future weather scenario. *Energy Build* 48:40–49.
543 <https://doi.org/10.1016/j.enbuild.2012.01.009>
- 544 Kershaw T, Eames M, Coley D (2011) Assessing the risk of climate change for buildings: A comparison between
545 multi-year and probabilistic reference year simulations. *Build Environ* 46:1303–1308.
546 <https://doi.org/10.1016/j.buildenv.2010.12.018>
- 547 Kolokotroni M, Giridharan R (2008) Urban heat island intensity in London: An investigation of the impact of
548 physical characteristics on changes in outdoor air temperature during summer. *Sol Energy* 82:986–998.
549 <https://doi.org/10.1016/j.solener.2008.05.004>
- 550 Kolokotroni M, Ren X, Davies M, Mavrogianni A (2012) London’s urban heat island: Impact on current and future
551 energy consumption in office buildings. *Energy Build* 47:302–311.
552 <https://doi.org/10.1016/j.enbuild.2011.12.019>
- 553 Maillard P, David F, Dechesne M, et al (2014) Caractérisation des îlots de chaleur urbains et test d’une solution
554 d’humidification de chaussée dans le quartier de la Part-Dieu à Lyon. *Tech Sci Méthodes* 6:23–35
- 555 Masson V (2000) A Physically-Based Scheme For The Urban Energy Budget In Atmospheric Models. *Bound-*
556 *Layer Meteorol* 94:357–397. <https://doi.org/10.1023/A:1002463829265>
- 557 Mavrogianni A, Davies M, Batty M, et al (2011) The comfort, energy and health implications of London’s urban
558 heat island. *Build Serv Eng Res Technol* 32:35–52. <https://doi.org/10.1177/0143624410394530>
- 559 Mavrogianni A, Wilkinson P, Davies M, et al (2012) Building characteristics as determinants of propensity to high
560 indoor summer temperatures in London dwellings. *Build Environ* 55:117–130.
561 <https://doi.org/10.1016/j.buildenv.2011.12.003>

- 562 Mitchell D, Heaviside C, Vardoulakis S, et al (2016) Attributing human mortality during extreme heat waves to
563 anthropogenic climate change. *Environ Res Lett* 11:074006. [https://doi.org/10.1088/1748-](https://doi.org/10.1088/1748-9326/11/7/074006)
564 9326/11/7/074006
- 565 Montazeri H, Blocken B, Hensen JLM (2015) Evaporative cooling by water spray systems: CFD simulation,
566 experimental validation and sensitivity analysis. *Build Environ* 83:129–141.
567 <https://doi.org/10.1016/j.buildenv.2014.03.022>
- 568 Munaretto F, Recht T, Schalbart P, Peuportier B (2017) Empirical validation of different internal superficial heat
569 transfer models on a full-scale passive house. *J Build Perform Simul* 0:1–22.
570 <https://doi.org/10.1080/19401493.2017.1331376>
- 571 Murray CJ (1994) Quantifying the burden of disease: the technical basis for disability-adjusted life years. *Bull*
572 *World Health Organ* 72:429–445
- 573 Murray CJL, Aravkin AY, Zheng P, et al (2020) Global burden of 87 risk factors in 204 countries and territories,
574 1990–2019: a systematic analysis for the Global Burden of Disease Study 2019. *The Lancet* 396:1223–
575 1249. [https://doi.org/10.1016/S0140-6736\(20\)30752-2](https://doi.org/10.1016/S0140-6736(20)30752-2)
- 576 Ortiz O, Castells F, Sonnemann G (2009) Sustainability in the construction industry: A review of recent
577 developments based on LCA. *Constr Build Mater* 23:28–39.
578 <https://doi.org/10.1016/j.conbuildmat.2007.11.012>
- 579 Peng RD, Bobb JF, Tebaldi C, et al (2011) Toward a Quantitative Estimate of Future Heat Wave Mortality under
580 Global Climate Change. *Environ Health Perspect* 119:701–706. <https://doi.org/10.1289/ehp.1002430>
- 581 Peuportier B (2004) Regen-Link -Site 4: La Noue Research Programme ENERGY, ENVIRONMENT AND
582 SUSTAINABLE DEVELOPMENT Thematic Priorities: ENERGY, Key Action 6, Economic and
583 Efficient Energy for a Competitive Europe Category of RTD project Demonstration. ARMINES
- 584 Peuportier B, Blanc Sommereux, I. (1990) Simulation Tool with Its Expert Interface for the Thermal Design of
585 Multizone Buildings. *Int J Sol Energy* 8:109–120. <https://doi.org/10.1080/01425919008909714>
- 586 Peuportier B, Millet J-R, Videau J-B, et al (2011) Groupe Scientifique sur le Confort d'Été, Rapport final. Centre
587 scientifique et technique du bâtiment (CSTB), 84 avenue Jean Jaures BP2, 77447 Marne-la-Vallée cedex
588 2
- 589 Peuportier B, Thiers S (2009) Les maisons passives sont-elles confortables ? écologiques ? CVC - Rev Clim
590 Jan/Fév:22
- 591 Polster B, Peuportier B, Blanc Sommereux I, et al (1996) Evaluation of the environmental quality of buildings
592 towards a more environmentally conscious design. *Sol Energy* 57:219–230.
593 [https://doi.org/10.1016/S0038-092X\(96\)00071-0](https://doi.org/10.1016/S0038-092X(96)00071-0)
- 594 Pomianowski M, Andersen CH, Heiselberg P (2015) Technical Potential of Evaporative Cooling in Danish and
595 European Condition. *Energy Procedia* 78:2421–2426. <https://doi.org/10.1016/j.egypro.2015.11.211>
- 596 Porritt S, Cropper PC, Shao L, Goodier CI (2012) Ranking of interventions to reduce dwelling overheating during
597 heat waves. *Energy Build* 55:16–27. <https://doi.org/10.1016/j.enbuild.2012.01.043>
- 598 Radhi H (2009) Evaluating the potential impact of global warming on the UAE residential buildings – A
599 contribution to reduce the CO2 emissions. *Build Environ* 44:2451–2462.
600 <https://doi.org/10.1016/j.buildenv.2009.04.006>
- 601 Roux C, Schalbart P, Peuportier B (2016) Development of an electricity system model allowing dynamic and
602 marginal approaches in LCA—tested in the French context of space heating in buildings. *Int J Life Cycle*
603 *Assess*. <https://doi.org/10.1007/s11367-016-1229-z>
- 604 Santé Publique France (2019) S'adapter à la chaleur dans un contexte de changement climatique

- 605 Schalbart P, Vorger E, Peuporter B (2021) Stochastic Prediction of Residents' Activities and Related Energy
606 Management. In: Ploix S, Amayri M, Bouguila N (eds) Towards Energy Smart Homes: Algorithms,
607 Technologies, and Applications. Springer International Publishing, Cham, pp 543–604
- 608 Seity Y, Brousseau P, Malardel S, et al (2011) The AROME-France Convective-Scale Operational Model. *Mon*
609 *Weather Rev* 139:976–991. <https://doi.org/10.1175/2010MWR3425.1>
- 610 Smith STh, Hanby VI, Harpham C (2011) A probabilistic analysis of the future potential of evaporative cooling
611 systems in a temperate climate. *Energy Build* 43:507–516. <https://doi.org/10.1016/j.enbuild.2010.10.016>
- 612 Synnefa A, Saliari M, Santamouris M (2012) Experimental and numerical assessment of the impact of increased
613 roof reflectance on a school building in Athens. *Energy Build* 55:7–15.
614 <https://doi.org/10.1016/j.enbuild.2012.01.044>
- 615 Tebaldi C, Hayhoe K, Arblaster JM, Meehl GA (2006) Going to the Extremes. *Clim Change* 79:185–211.
616 <https://doi.org/10.1007/s10584-006-9051-4>
- 617 Tham S, Thompson R, Landeg O, et al (2020) Indoor temperature and health: a global systematic review. *Public*
618 *Health* 179:9–17. <https://doi.org/10.1016/j.puhe.2019.09.005>
- 619 van Hooff T, Blocken B, Hensen JLM, Timmermans HJP (2014) On the predicted effectiveness of climate
620 adaptation measures for residential buildings. *Build Environ* 82:300–316.
621 <https://doi.org/10.1016/j.buildenv.2014.08.027>
- 622 Voldoire A, Sanchez-Gomez E, Salas y Mélia D, et al (2013) The CNRM-CM5.1 global climate model: description
623 and basic evaluation. *Clim Dyn* 40:2091–2121. <https://doi.org/10.1007/s00382-011-1259-y>
- 624 Wan KKW, Li DHW, Liu D, Lam JC (2011) Future trends of building heating and cooling loads and energy
625 consumption in different climates. *Build Environ* 46:223–234.
626 <https://doi.org/10.1016/j.buildenv.2010.07.016>
- 627 Wang X, Chen D, Ren Z (2010) Assessment of climate change impact on residential building heating and cooling
628 energy requirement in Australia. *Build Environ* 45:1663–1682.
629 <https://doi.org/10.1016/j.buildenv.2010.01.022>
- 630 Weidema BP, Bauer C, Hischer R, et al (2013) Overview and methodology: Data quality guideline for the
631ecoinvent database version 3. Swiss Centre for Life Cycle Inventories
- 632 Williams AA, Spengler JD, Catalano P, et al (2019) Building Vulnerability in a Changing Climate: Indoor
633 Temperature Exposures and Health Outcomes in Older Adults Living in Public Housing during an
634 Extreme Heat Event in Cambridge, MA. *Int J Environ Res Public Health* 16:2373.
635 <https://doi.org/10.3390/ijerph16132373>
- 636 Williams D, Elghali L, Wheeler R, France C (2012) Climate change influence on building lifecycle greenhouse
637 gas emissions: Case study of a UK mixed-use development. *Energy Build* 48:112–126.
638 <https://doi.org/10.1016/j.enbuild.2012.01.016>
- 639