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Influence of climate change on summer cooling costs and heat stress in urban office buildings

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Abstract

Indoor climatic conditions are strongly influenced by outdoor meteorological conditions. It is thus expected that the combined effect of climate change and the urban heat island effect negatively influences working conditions in urban office buildings. Since office buildings are particularly vulnerable to overheating because of the profound internal heat gains, this is all the more relevant. The overheating in office buildings leads to elevated cooling costs and, because additional work breaks are required by legislation, productivity losses. We have developed a methodology incorporating urban climate modelling and building energy simulations to assess cooling costs and lost working hours in office buildings, both for current-day and future climate, extending towards the end of the 21th century. The methodology is tailored to additionally assess the impact and benefits of adaptation measures, and it is designed to be transferable from one city to another. Results for a prototype building located in three different European cities (Antwerp, Bilbao and London) illustrate the challenge in keeping Western-European office buildings without appropriate adaptation measures comfortable by the end of the 21th century, and the beneficial effect of adequate adjustments.

Key words: Climate change, heat stress, worker productivity, indoor climate, cooling costs

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1. Introduction

The world's climate is changing and the changes will have a major impact on Earth's population. Global climate models (GCMs) predict an overall increase in air temperature and, consistently, also a rise of the number, frequency and intensity of adverse effects, such as heat waves (Meehl and Tebaldi 2004; Diffenbaugh and Giorgi 2012; IPCC et al. 2013). Cities are heavily vulnerable to these adverse consequences as they already experience enhanced heat stress because of an urban warming process generally referred to as the urban heat island (UHI) phenomenon (Oke 1973; Oke 1982). Given that cities are home to more than half of the world's population and concentrate infrastructure and economic activity, this is all the more relevant.

Indoor thermal comfort and building energy demand are heavily influenced by the outdoor thermal environment (Hensen and Lamberts 2011; ASHRAE 2013), and it is thus expected that the combined effect of climate change and the UHI-effect will result in impacts on the indoor ambient temperatures of buildings, especially during summer. In recent years, the current and future heat balance of residential and office buildings has received significant attention in academic research (de Wilde and Coley 2012; Buchin et al. 2016). Compared to residential buildings, office buildings experience larger internal heat gains due to the metabolism of the office workers, the high installed power for office lighting and the heat dissipation of the electrical office equipment. Offices are therefore referred to as "internal load dominated" (ASHRAE 2013). Because of the high internal heat gains, there is a significant risk for overheating effects, especially during summer months in unadapted buildings (Guan 2006; Jentsch et al. 2008; Li et al. 2012).

The study at hand focuses on office buildings, either equipped with a cooling system or 'free-running', i.e. without active cooling equipment. In the latter type of buildings, unfavorable conditions due to overheating have an important influence on the wellbeing and the productivity of the office workers (Leaman and Bordass 1999; Seppänen et al. 2003; Berger et al. 2014). If these adverse conditions become too severe, precautions are demanded according to international and national legislations. ISO-standards require additional work breaks if (workplace) climatic conditions deteriorate, causing lost working hours and economic losses (Kjellstrom et al. 2009). One possible measure to guarantee favorable indoor thermal conditions, is to equip the building with an active cooling system. Cooling energy demands in such buildings will however rise significantly over the course of the 21th century (Li et al. 2012).

In this paper, we present a methodology to study the evolution of both the summer cooling demand and the lost working hours related to the excess heat stress in (respectively) an actively cooled and a 'free-running' prototype urban office building during the 21th century. The methodology furthermore allows us to analyze the effectiveness of adaption measures in reducing the negative effects of climate warming. The remainder of this paper is organized as follows. In the second section the methodology is introduced, while the third section introduces the adaptations measures considered in this work. The methodology outlined in this paper is in general applicable to any European city. The applicability is mainly illustrated by model results for the city of Antwerp in Belgium in the fourth section. To show the transferability of the methodology, a comparison between office buildings in Antwerp (Belgium), Bilbao (Spain) and London (UK) will be provided. In section 5, the results and the limitations of the methodology are discussed.

2. Methodology

A. Overview

The methodology outlined in this paper consists of two major steps, the urban climate modelling and the building energy simulation, followed by several minor steps, leading finally to lost working hours and cooling demands for a prototype building. The full methodology is visualized in Figure 1.

In the first major step, outdoor urban climatic variables (amongst other temperature and wind speed) are calculated using the UrbClim urban climate model (De Ridder et al. 2015). UrbClim scales large-scale weather input data down to agglomeration-scale and computes the impact of urban development on the most important weather parameters (air temperatures, land surface temperatures, wind speeds and humidity). The model has been validated for various cities with hourly temperature measurements; validation campaigns have amongst others focused on London (United Kingdom), Bilbao (Spain), Antwerp (Belgium), Berlin (Germany) and Paris (France) (De Ridder et al. 2015;

Zhou et al. 2016). Focusing on the northern hemisphere summer period, we model the urban outdoor climate between May and September (both included). To assess the influence of climate change, we study both the current climate (reference period 1986 – 2005), and the near (2026 – 2045) and far future (2081 -2100). We use time periods of at least twenty years to ensure that the interannual variability is correctly taken into account. The current climate is modeled by coupling UrbClim to large-scale meteorological ERA-Interim reanalysis data (Dee et al. 2011) of the European Centre for Medium-Range Weather Forecasts (ECMWF). To study the future urban climate, UrbClim has been coupled to the output of an ensemble of eleven global climate models (GCMs) contained in the Coupled Model Intercomparison Project 5 (CMIP5) archive of the Intergovernmental Panel on Climate Change (IPCC) (Lauwaet et al. 2015). The IPCC identifies four climate scenarios (called Representative Concentration Pathways, RCP), ranging from very strong mitigation scenarios (RCP2.6) to a business-as-usual scenario (RCP8.5). Due to CPU-limitations, only the RCP8.5 scenario will be considered in this study. Although this is the scenario with the largest warming potential, current emission trends continue to track along the trends of this scenario (Peters et al. 2013). In the study at hand, to reduce computational time, we have only coupled UrbClim to the output of one GCM, the GFDL-ESM2M model of NOAA (Dunne et al. 2012). This model was selected since, among the 11 GCMs that have been considered, it yields the median warming of the mean temperature for the three cities under investigation (Lauwaet et al. 2015).

The outdoor climatic data are subsequently used as input for the building energy model EnergyPlus, a state-of-the art building energy analysis software which is managed by USA National Renewable Energy Laboratory (NREL). EnergyPlus simulates the energy management and indoor climate of individual buildings by performing hour-by-hour computations of internal and external heat fluxes (Crawley et al. 2001; Henninger et al. 2004; Crawley et al. 2008). In this study, EnergyPlus is used to model two versions of a prototype building, which only differ in the presence or absence of an active cooling system, but are otherwise identical. For the former building, we are interested in the cooling costs required to keep the temperature below a constant threshold value. Inside the building without active cooling, temperatures can increase unlimitedly, causing overheating and, during episodes of extreme heat stress, worker breaks are required according to international guidelines. In this work, we determine the amount of lost working hours based on the US ACGIH non-acclimatized standard by the National Institute for Occupational Safety and Health. The resulting lost working hours and energy demands feed into a macro-economic analysis of the economic loss due to heat stress in summers, which is the subject of a separate paper (Costa et al. 2016) and a project report (Costa and Floater 2015).

B. Prototype building

The case study model under investigation is a typical Western-European, recently built five story office building. The generic typology can be considered representative for contemporary building praxis. Results for cooling demands and lost working hours refer to the third story of this building. The floors above and below are assumed to have an identical temperature and occupancy profile, consequently there is no net resulting heat flux between the two stories. Due to the elevated location of the 3th floor office, shadowing effects of parking lots, small trees, etc. can be neglected, and it is assumed that the building receives no shadow from surrounding buildings or larger trees. The third floor of the office building is subdivided into four thermal zones. Within a single zone, the air temperature is assumed to be uniform. Two office zones are located at the perimeter, one oriented North and the other South. A third office zone without external windows is located in the core of the building. A fourth zone comprises the auxiliary functions such as staircases and elevators. The ventilation rate for the three office spaces is assumed to be 22 m³/h/person during office hours, which corresponds to IDA class 3: “Moderate indoor air quality” according to European standards (EN 13779:2007). In the actively cooled building, the standard thermostats setpoint is 25°C. More details on the dimension and the structural properties of the building are provided in the supplementary material

C. HVAC energy demand

The energy demand of the HVAC system during summer operations consists of two parts: the ventilation demand and the cooling system demand. The latter depends on the temperature in the office building, and hence differs hour after hour. The energy consumption of the ventilation scheme, on the other hand, is independent of the climatic variables since the ventilation rates are assumed to be fixed values. Both the cooling and ventilation energy demand of the entire office floor are standard output fields of the EnergyPlus model. Due to the nature of the cooling system and the interzonal heat exchanges, it is impossible to disentangle the costs for the different rooms. In the remainder, we therefore always provide ventilation and cooling costs for the entire third floor.

D. Lost working hours

The calculation of the lost working hours is based upon the US ACGIH (Association Advancing Occupational and Environmental Health) non-acclimatized standard by the National Institute for Occupational Safety and Health (NIOSH), which demands additional working breaks if the heat stress at the workplace surpass a threshold. The length of the breaks and the level of the thresholds depends on the activity of the worker (Costa and Floater 2015). Since the paper at hand focuses on office buildings, the details for the lowest worker intensity class is used. The US ACGIH-thresholds make use of the wet bulb globe temperature (WBGT), which is a composite temperature used to estimate the effect of temperature, humidity, wind speed and (direct and thermal) radiation on humans (Yaglou and Minard 1956; Budd 2008). Multiple methods exist to estimate the WBGT from standard meteorological variables (Lemke and Kjellstrom 2012). Here we opt for the semi-empirical formula of Bernard (Bernard and Pourmoghani 1999). The WBGT-calculation has been validated using a measurement campaign in Ghent, Belgium (Lauwaet et al. 2017).

According to the US ACGIH standard non-acclimatized functions, the fraction of lost working hours, LWH, as a function of the WBGT, is

$$LWH = \begin{cases} 0 & WBGT < 27.6^\circ\text{C} \\ 0.0204\,(WBGT)^2 - 0.9794\,WBGT + 11.474 \ \text{ if } & 27.6^\circ\text{C} < WBGT < 31.9398^\circ\text{C} \\ 1 & WBGT > 31.9398^\circ\text{C} \end{cases}$$

Hence, if the WBGT is smaller than 27.6°C, normal work takes place all the time, while the worker has to rest during a (non-zero) fraction of the time if the threshold of 27.6°C WBGT is exceeded. When 31.9398°C WBGT has been reached, work can no longer resume.

3. Adaptation measures

The methodology is also suited to analyze the efficacy of soft and hard adaptation measures. In this work, we focus on adaptation measures that decrease the exposure to unfavorable circumstances, either by increasing comfort or decreasing the time workers spent in uncomfortable conditions. For the soft measures, the focus lies on adapted working hours, including (early) morning and (late) evening work, and a combination of both. The seven working regimes applied in the study at hand are introduced in Table 1. These measures are based on the similarity with current practices in Europe; the morning working scheme is for instance similar to existing measures for public workers during summer in Spain. Whereas the soft adaptation measure focuses on avoiding the presence of workers during the hottest moments of the day, the hard adaptation measures mainly deal with improving indoor conditions. Firstly, we study the use of solar blinds at the outside of the building. These blinds are sun blocking screens that automatically lower if the irradiance on the windows is larger than a certain threshold value (in this example set to 75 W/m^2), thereby effectively reducing the incoming solar radiation. Secondly, the rate of the mechanical ventilation is increased from 22 $m^3/h/p$ to 50 $m^3/h/p$, which corresponds to IDA class 3: "Medium indoor air quality" according to European standards (EN 13779:2007). Thirdly, in the base line set-up, the mechanical ventilation is reduced during the night (to 25% of the rate during the day, being 5.5 $m^3/h/p$), in order to reduce the ventilation costs. We instead propose to keep the ventilation during the night at the same rate as during the day (at 22 $m^3/h/p$), causing lower cooling demands during the day. All the foregoing adaptation measures can be applied in buildings without and with air-conditioning. In the latter case, changing the setpoint temperature of the cooling system provides an additional way to reduce the cooling demand. We investigate the effect of increasing the maximally allowed temperature in the building from 25°C to 31°C.

4. Results

A) Antwerp during the reference period: energy demand

We first focus on the HVAC-cost in an actively cooled building during the reference period (1986 – 2005) in Antwerp, and compare the results for the different hard adaptation measures. For simplicity, we assume that the workers use the baseline working hours. Figure 2 shows the average yearly cooling and ventilation demand during summer in the course of the reference period. Adding up the ventilation and the cooling demand for the base case building, a total energy demand just over 6200 kWh per summer is observed. All adaptation measures considered in the study reduce the total energy costs, but the effectiveness varies greatly between the different options. Increasing the ventilation rate significantly reduces the cooling demands, but since the ventilation cost more than doubles, the net effect is a minor reduction by 7%. Adding solar blinds or increasing the nocturnal ventilation have more or less the same effect on the total energy demand. The latter option cuts the cooling costs by 40% percent, but due to the higher ventilation costs, the total energy demand is only reduced by 23%. Although the reduction in cooling costs is lower when (external) solar blinds are added, there are no increases in ventilation costs and so the total energy demand is reduced by 28%. The largest effect is obtained by increasing the thermostat setpoint. In this way, the cooling costs are more than halved.

B) Antwerp during the reference period: lost working hours

Figure 3 shows the fraction of lost working hours (LWH) during the summer period (May - September) during an average year in the reference period (1986 - 2005). Since indoor temperatures are different for the north and the south facing rooms (as both experience a different irradiance), the LWH will also differ. Using the base line working hours the LWH in the south facing room is larger than 4%, while in the north-facing room only 1% of the working hours is lost. This large difference between both zones indicates that building orientation and zoning in office rooms are adaptation measures to consider, as is moving workers to cooler rooms during episodes of heat stress. Moreover, the inter-annual spread is quite large. For the south facing room, during the year with the minimal loss, only 0.3% of the working hours are lost, while during the year with the highest loss, work has to be interrupted during 12% of the time.

Figure 3 also shows the effectiveness of the modified working regimes. For the north-facing room, the absolute gain is rather limited, as the LWH is already small for the base line working hours. For the south facing room, all the adapted working schemes have a significant beneficial effect. The benefits of the morning schedules are generally larger than those of the evening work, but the best results are obtained for the combination of early morning and late evening work (7 – 11, 17 – 20). This scheme reduces the LWH to under 2%. Finally, those working with the morning-evening schedule in the south-facing room are still much more exposed to heat stress than employees in the north-facing room using the base line working hours. Hence, it is more beneficial to invest in moving workers to cooler places in the building, than in modified working hours.

We only consider two hard adaptation measures in relation with lost working hours, namely increased ventilation and solar blinds. Results are shown in Figure 4, in which we again focus on the south-facing room. The hard adaptation measures have a much larger effect than the soft adaptation measures: whereas the soft measures can at most reduce the LWH to 1.9% (for the morning-evening work), both hard adaptation measures reduce the loss to well below 1%. With solar blinds the LWH can be lowered to 0.8%, while the increased ventilation system reduces the loss to 0.12%.

C) Antwerp during the near and far future

Figure 4 shows the LWH and cooling costs in Antwerp for the near (2026 – 2045) and the far future (2081 - 2100). Results are averages over the twenty years periods. We anew only focus on results for the summer period (May – September), and thus implicitly assume that no lost working hours or major cooling costs occur in the other months. While this is certainly a correct assumption for the contemporary situation and the near future, it may no longer be valid for the far future. Hence, the end-of-the-century results are actually underestimated.

As expected, the cooling costs and the LWH increase between the current period and the future periods. For both quantities, the largest increase is observed between the near and the far future, while the increment between the reference period and the near future is much smaller. The effects for the LWH are also much larger than those for the cooling costs, since the LWH is more sensitive to temperature variations. Over the course of the 21th century, the LWH quadruples for the base case building. The two hard measures considered in this study serve as examples of effective adaptation: both the increased ventilation and the solar blinds significantly decrease the LWH at the end of the century. In the prototype base case building with cooling system, the energy demand increases by 25% from 6200 kWh to 7800 kWh over the course of the 21th century. The increases for the adapted buildings are more or less similar, but the exact results depend on the adaptation measure.

D) London and Bilbao during the reference period

Figure 5 shows the cooling demands and the LWH (for the south-facing room) for Bilbao, London and Antwerp, during the reference period, for the unadapted building and base line working hours. The heat stress is, as expected, much higher in Bilbao, while results for London and Antwerp are more or less similar. The difference between the cooling costs in Antwerp and London is below the uncertainty margin of this study, but there is a significant difference in the LWH, although it is a rather small discrepancy. The cooling demand is much higher in the lower-latitude city Bilbao, where the average demand is 1.6 times as large as the one in Antwerp and London. Anew the difference is more profound for the fraction of lost working hours, for which the values in Bilbao are six times larger than those in Antwerp. These large differences for the lost working hours are mainly related to the threshold-based nature of the indicator, which is very sensitive to small temperature increases. Additional results concerning the climate change and adaptation measures in London and Bilbao have been discussed in a project report (Costa and Floater 2015).

5. Discussion and limitations

The results for a prototype building substantiates the significant influence of climate warming on indoor climate and cooling costs in office buildings. The number of lost working hours in the building without active cooling quadruples between the reference period and the far future, if emissions keep tracking along the RCP8.5-scenario. It is hence challenging to keep Western-European ‘free-running’ office buildings without appropriate measures comfortable by the end of the 21th century. A similar conclusion has been reported earlier for buildings in the UK (Jentsch et al.

2008). We observe much larger negative effects for a similar building in Bilbao, where additional work breaks are 6 times as frequent as those in Antwerp. Well-suited adaptation measures reduce the risk of overheating in our prototype building significantly. In this study we have observed that, for our prototype building, the benefits of hard measures by far outweigh those of the soft measures. The most effective adaptation measures deal with solar blinds and increased (active) ventilation, which respectively reduce the amount of lost working hours by approximately 60% and 90% for the far future period. Moreover, moving employees within the prototype building has a significant positive effect, reducing the number of lost working hours by 75%. Previous studies have also observed these positive effects in other prototype office buildings: the overheating risk in a south-facing room in a UK office building has been found to be twice as large as the same risk in a north-facing room (de Wilde and Tian 2010), and also the beneficial effects of external shading (Frank 2005; Atzeri et al. 2014) and well-designed ventilation strategies (Gratia and De Herde 2004; Jentsch et al. 2008), including nightly ventilation (Kolokotroni and Aronis 1999), have been described. In case hard adaptations are technically unfeasible, soft measures such as adapted working hours provide an alternative. In our prototype building, the largest beneficial effects are observed for a schedule with a morning (7:00 – 11:00) and a late afternoon (17:00 – 20:00) working shift. This morning-evening working schedule halves the lost working hours, but it has a substantial influence on the life style of the workers, and reducing the heat stress in office buildings using soft measures thus entails a trade-off between work-life balance and economic considerations.

Installing an active cooling system with a fixed threshold temperature nullifies the overheating risk. However, operational costs of such a device will drastically increase over the course of the 21th century. For our prototype building, cooling demand increases with 25% by 2100. The HVAC-costs are significantly reduced by applying suited adaptation measures. The largest potential cost reduction is associated with higher setpoints values: in the prototype building, cooling demands are more than halved by increasing the setpoint from 25 degrees to 31 degrees. Such a measure however comes at the cost of higher discomfort for the workers (Roaf et al. 2011). Other successful adaptation measures include external shading or changes in the building ventilation scheme; for our prototype building, adding external solar blinds is the most effective measure, as it reduces the cooling costs by approximately 30%. These large benefits of installing external shading in office buildings have been identified before in numerous studies (Gratia and De Herde 2004; van Moeseke et al. 2007; Atzeri et al. 2014; Mavrogianni et al. 2014).

The results highlight the limitations of adaptation measures that focus on decreasing the exposure to uncomfortable indoor conditions. Although new building design options (including new materials and more efficient HVAC-systems) will provide benefits that are larger than the ones cited in this work, there will always be an upper limit on the effectiveness of the adaptation options. To achieve a greater impact, the measures related to a decrease in exposure should be complemented with measures related to raising the threshold temperatures for thermal comfort. The latter category contains options such as raising awareness and ‘personal’ measures to increase the thermal comfort threshold (as for instance adapted clothing and modified behavior during high heat-stress periods).

Identifying the appropriate methodology for conducting the current assessment is challenging. As such, our study is based on a number of assumptions that limit the generalization of the results. Amongst other, our approach is limited because of the use of the following assumptions:

- The actual productivity loss due to heat stress is underestimated in this methodology, since only the lost working hours due to legally compulsory actions (according to US ACGIH standards) are taken into account. In reality, productivity losses are observed at much lower temperatures due to the maladaptation of the workers to heat stress.
- The standards in the current work do not take adaptation to changing conditions into account, since most legislation concerning additional work breaks is based on fixed thresholds. Recent studies point at the need of adaptive thermal standards, since, in case of

discomfort, people react in ways to restore their comfort, resulting in a continuously changing comfort temperature (de Dear and Brager 1998; Nicol and Humphreys 2002).

- Only one prototype building has been used, and many assumptions have been made in designing this building. Thermal properties of buildings vary greatly, and a broader analysis should use different buildings typologies. When discussing the future productivity loss and cooling costs, we furthermore ignore any major renovations of the buildings. It is highly unlikely that HVAC-systems or building design will still be the same by the end of the 21st century. These modifications are ignored, as the framework is currently used to assess the “pure” effect of climate change, i.e. what would happen if building practices are unchanged.
- Although the IPCC identifies four Representative Concentration Pathways, we have only used the scenario with the largest warming (RCP8.5). Moreover, in contrast with the traditional deterministic approach of the RCPs, recently probabilistic climate projections (for instance using weather generators) have emerged. For computational reasons, these have not been considered in the current work.
- Only a limited selection of adaptation measures has been applied. A wide ranch of alternatives have been described in literature, including, amongst others, reduction in internal heat gains (Collins et al. 2010), technical improvements in the performance of cooling and ventilation devices (Sclafani 2010) and relocation of office workers (de Wilde and Tian 2010).

Many of the premises listed are related to the high CPU-requirement of the study. Since the general methodology is flexible and easily customizable for other set-ups and applications, these limitations could be addressed with additional simulations and minor modifications to the methodology.

In sum, we have introduced a general methodology to assess cooling costs and lost working hours caused by overheating in office buildings, both for the current-day situation and future periods extending towards the end of the 21th century. Using the same methodology, the efficacy of adaptation measures can be assessed. The analysis of a prototype building and three case study cities demonstrate the substantial influence climate warming will have on indoor climatic conditions and energy demand in office buildings, and the beneficial effects of targeted adaptations measures. Although the results for this prototype building should not be generalized, the methodology is easily transferable and adaptable for different set-ups, including others cities, prototype buildings and adaptation measures.

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Figures

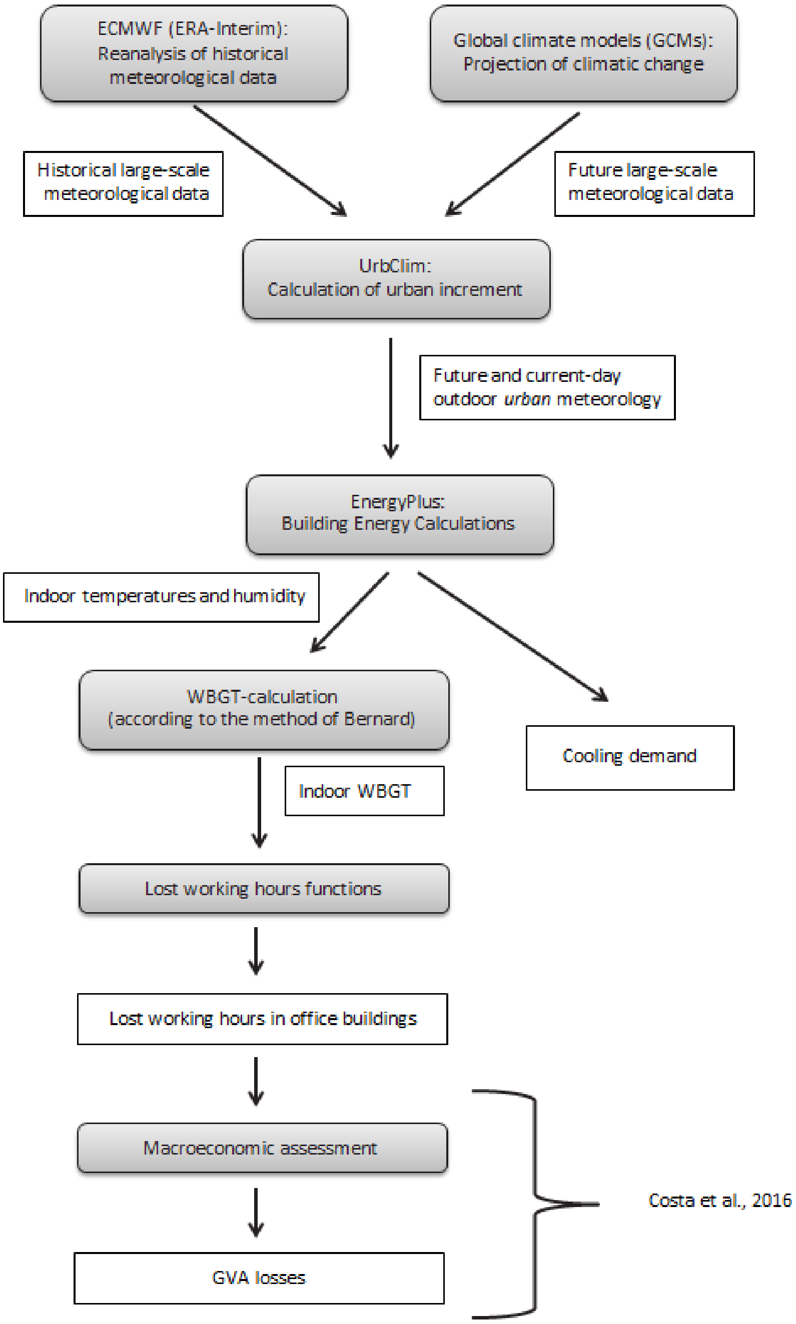

Figure 1: General overview of the methodology. The top part of the figure illustrates the part of the methodology described in this paper, more details on this are provided in the main text. The bottom part illustrates the link to the follow-up macroscopic economic analysis provided in (Costa et al. 2016). *Models and calculations are indicated in shaded boxes, while data is indicated in unshaded ones.*

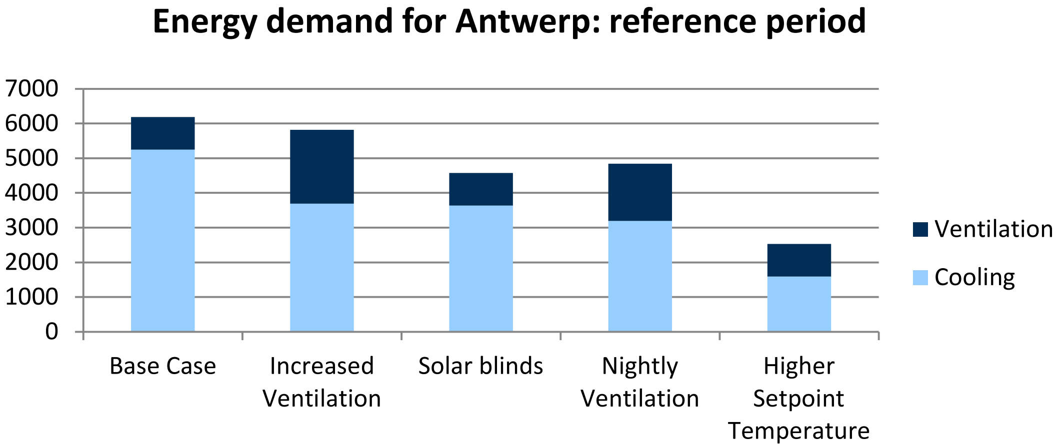

Figure 2: Cooling and ventilation demand for Antwerp during the reference period (1986 – 2005), in a building in which workers use the base line working hours (in kWh per year).

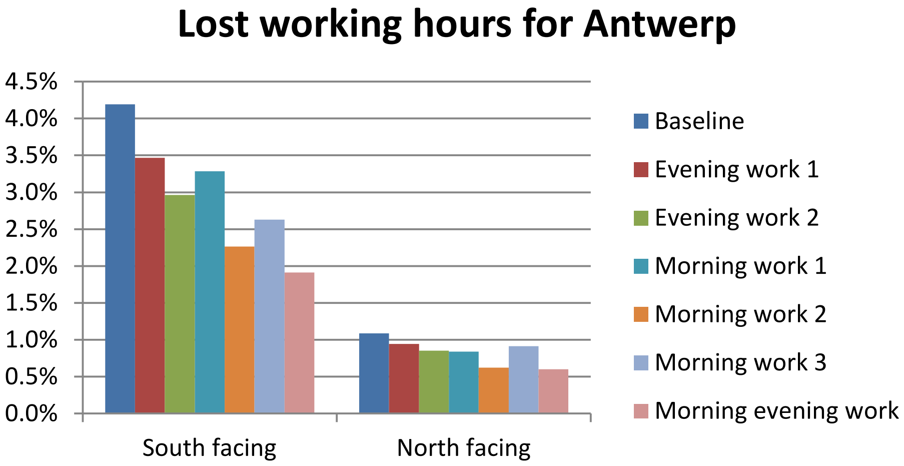

Figure 3: Lost working hours for Antwerp during the reference period (1986 – 2005) for different worker regimes. The figures provides results for the north- and the south-facing room separately. The figure shows the fraction of working hours that get lost during an average summer (May – September).

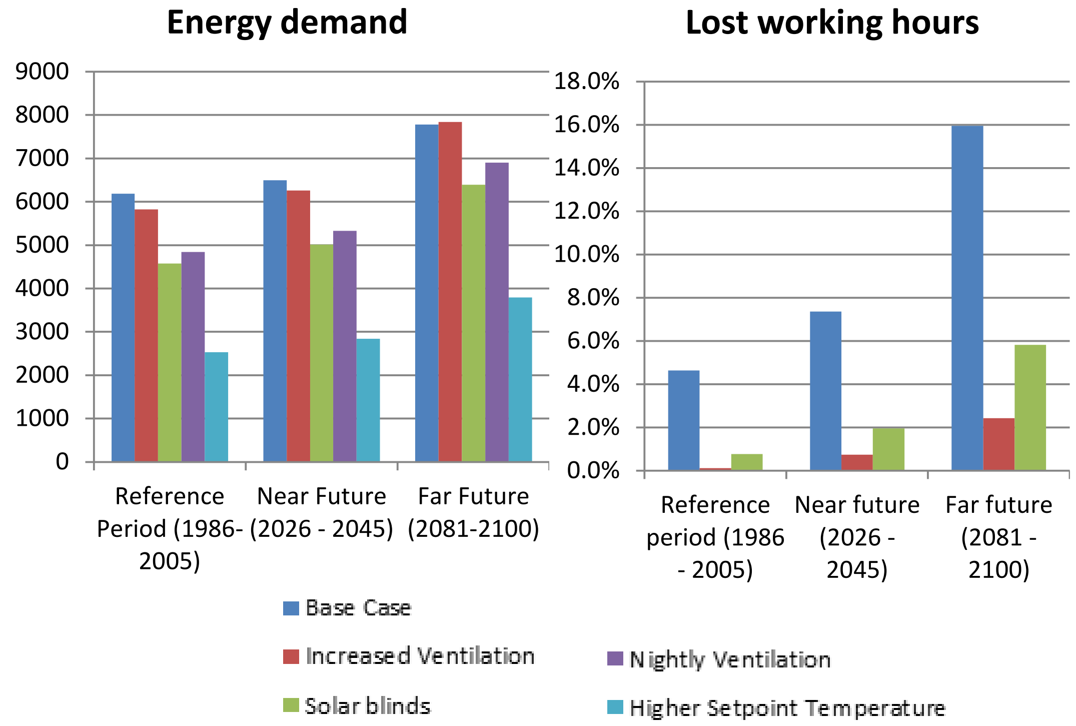

Figure 4: Time evolution of the building energy demand and lost working hours in Antwerp, for a building in which the workers use the base line working hours. The right figure provides fraction of lost working hours in the south-facing room during an average summer (May – September). The left figure shows the total energy demand (cooling and ventilation) during an average summer(in kWh per year).

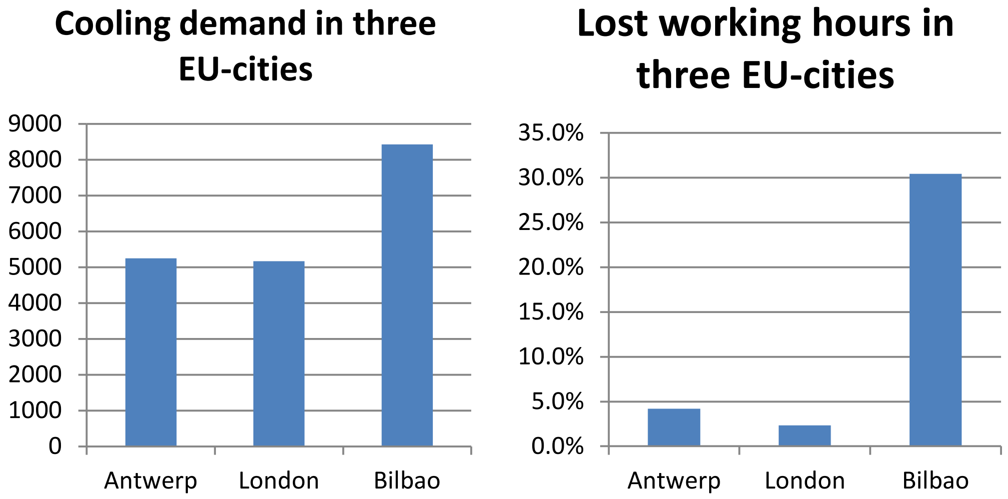

Figure 5: Cooling demand (left, in kWh per year) and fraction of lost working hours for the south-facing room (right) for the reference period in the three EU-cities under consideration. The results are obtained using the base case prototype building (without any adaptations measures), and using the base line working hours.

Tables

Name	Working hours
Baseline	9 – 13, 14 – 17
Evening work 1	9 – 13, 15 – 18
Evening work 2	9 – 13, 16 - 19
Morning work 1	8 – 12, 14 – 17
Morning work 2	7 – 12, 15 – 17
Morning work 3	6 – 13
Morning and evening work	7 – 11, 17 – 20

Table 1: List of the working regimes applied in this study.

Supplementary material: building details

In this supplementary material, some details concerning the prototype building are elaborated. Figure 6 visualizes the prototype building and its third floor. *Table 2* provides the main dimensions of the building, and *Table 3* provides some characteristics.

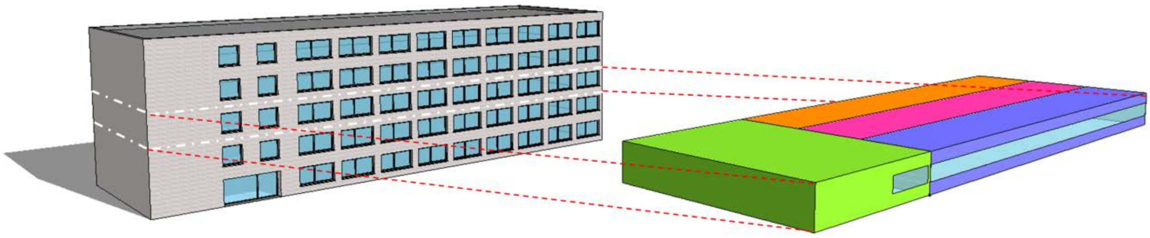

Figure 6: Graphical representation of the building with a zoom on the third floor which consists of four interconnected thermal zones.

Dimension	Surface
Floor (Ceiling)	1080m^2
Lay-out of third floor	4 thermal zones, 270 m^2 each
External facade	530.40 m^2
Size of windows	152.96 m^2 - 136 m^2 glass (office zones: 61.20m^2 each, auxiliary zone: 13.6m^2) 16.96m^2 frame

Table 2: Building dimensions.

Property	Value
External facade	Masonry U-value = 0.201 W/m^{2}K
Insulation	10 cm rigid polyurethane foam λ = 0.0245 W/mK
Thermal properties of windows	U_{glass} = 1.199 W/m^{2}K U_{frame} = 1.199 W/m^{2}K $SHGC_{glass}$ = 0.389
Air infiltration through external facades	0.4 m^3/h per square meter
Internal thermal gains	Artificial lighting : 10 W/m^2
	Office equipment : 7.5 W/m^2
Occupancy	50 m^3/h/person (10 m^2 of office space available per worker)

Table 3: Main building characteristics.