



## **RAMSES PROJECT**

*Grant Agreement n° 308497*

### **WP 5: Development of a cost assessment framework for adaptation**

#### **Economic costs of climate change in European cities**

**Cost and economic data for the European Clearinghouse databases**

**Reference code: RAMSES – D5.2**

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**Short Description:**

This report presents a new transferable methodology for estimating economy-wide production losses from climate change impacts such as heatwaves and flooding, together with averted losses from adaptation measures. Results for RAMSES core case study cities (London, Antwerp and Bilbao) are presented as cost data for the RAMSES common platform.

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## List of Acronyms

CES: Constant Elasticity of Substitution

CMIP5: Coupled Model Intercomparison Project 5

ECMWF: European Centre for Medium-Range Weather Forecasts

EUROSTAT: European Union Directorate General of Statistics

GCM: Global Climate Models

GFCF: Gross Fixed Capital Formation

GVA: Gross Value Added

IPCC: Intergovernmental Panel on Climate Change

ISO: International Organization for Standardization

NACE: Statistical classification of economic activities in the European Community

NIOSH: National Institute for Occupational Safety and Health

ONS: UK Office for National Statistics

RCP: Representative Concentration Pathways

WBGT: Wet Bulb Globe Temperature

# 1 Executive Summary

Cities are particularly vulnerable to climate change given the concentration of people, assets, infrastructure and productive activities in urban areas. However, few methodologies currently exist for assessing city-wide impacts of climate change and the associated costs of adaptation. In line with the overarching goals of RAMSES, the aim of this report is to set out a transferable methodology for generating data on the economic costs of climate change impacts in cities.

In the first part of this report, we develop an economic cost methodology to assess the impact of specific climate change hazards through different channels of urban productive activity. The methodology is based on the premise that each hazard affects one or more parameters of city production in different sectors, and estimates their overall impact through this particular channel. We demonstrate the methodology by examining the impact of urban heat waves on productivity loss and how the reduction in productivity leads to production losses across sectors of the city economy. Our approach allows us to assess various characteristics of urban production, including the flexibility of the productive system in terms of the degree of substitution between labour and capital, its labour intensity, and the relative importance of different sectors in the economy.

Initial results suggest that the impacts of heat on the urban economy are highly variable and depend on characteristics of production, such as the elasticity of substitution between capital and labour, and the sectoral division of production. We estimate that in a warm year in the far future (2081-2100) the total losses to the urban economy could range between 0.4% of Gross Value Added (GVA) for London and 9.5% for Bilbao in the absence of adaptation. In addition to differences in temperatures, the structure of the city's economy – in terms of the size of different sectors of the economy - has a major influence on the magnitude of damages, with large urban construction sectors being particularly vulnerable to heat effects. The averted losses due to adaptation measures such as behaviour change, air conditioning, ventilation, insulation and solar blinds range from -€314 million to over €23,004 million.

In the second part of this report, we examine a range of other channels through which the city economy may be impacted by climate change hazards. These include effects of heat stress on rail buckling and associated transport disruption, the impact of heat on direct health costs, the impact of pluvial flooding on transport disruption, and damage costs and adaptation costs and benefits of sea flooding. These costs draw on a range of RAMSES work packages, including WP1, WP2, WP3, WP4 and WP6.

The cost methodology not only provides estimates of production costs from increasing temperatures or extreme heat and flooding events, but also highlights the vulnerability of different economic sectors and the key mechanisms affecting production losses. This is important for identifying the most effective climate change adaptation strategies. Moreover, the methodology is relatively transferable to different urban contexts with minimal requirement of economic data or proxy values. Our approach is a step towards a more clear view on categorizing costs. Nevertheless, it is subject to a number of uncertainties that require assumptions, which cannot easily be resolved.

The cost data in this report have been uploaded to the RAMSES common platform, including several rich datasets in terms of costs at the city level of climate change hazards, as well as benefits (averted losses) and costs of adaptation.

## **2 Introduction**

Cities represent concentrations of people, assets, infrastructure and productive activities, and as a consequence, the socio-economic costs of climate change are predicted to be high in urban areas. However, climate-related impacts such as extreme heat and flooding have complex consequences and vary greatly between cities and even within urban centres. In addition, data at the city level are often scarce, inaccessible and difficult to compare between cities. As a consequence, the extent of future economic losses in cities is challenging to quantify, and few methodologies currently exist for assessing city-wide impacts of climate change and the associated costs of adaptation. If policy makers are to implement measures to adapt to heat waves, flooding and other climate-related hazards in cities, a better understanding of the scale of damages and the effectiveness of different adaptation strategies is required.

### ***2.1 Objectives of this report***

The overall aim of this report is to set out a transferable method for generating data on the economic costs of climate change impacts in cities. City-wide costs were generated for London, Antwerp and Bilbao, the three core case study cities of the RAMSES project. These costs, together with damage costs generated from WP1, WP3 and WP6 of the RAMSES project, and have been uploaded onto the RAMSES Common Platform database which will be linked to the European Clearinghouse database, ClimateAdapt (<http://climate-adapt.eea.europa.eu/>).

In this report, we develop an economic cost methodology through which the costs of various climate change hazards, acting through different channels, can be evaluated. We focus on the effect a climate hazard has on inputs of the production activity – for example, by decreasing capital or labour levels, or reducing their productivity – to work out the overall effect to urban production. By focusing on one hazard and one channel through which it affects costs at a time, the model remains tractable, which facilitates the interpretation of the results. This is vital for identifying the most effective climate change adaptation strategies.

One of the overarching goals of RAMSES is to deliver quantified evidence of the impacts of climate change with a focus on cities, as well as of the costs and benefits of a wide range of adaptation measures. This deliverable constitutes a step forward in providing a clearer methodology for quantifying these costs.

### ***2.2 Economic cost methodology***

Deliverable 5.1 of the RAMSES project, “Review of climate change losses and adaptation costs for case studies” identified climate threats that are predicted to impact on cities. The review showed that cities are vulnerable to heat waves, retaining high temperatures for longer periods than surrounding areas (the urban heat island effect), vulnerable to flooding due to sealed surfaces such as roads and pavements found in urban areas. In this report, we examine the costs of heat and flooding in more detail.



We first set out the economic cost methodology using the case of heat and productivity: we examine the effects of heat stress on the urban economy through its impact on labour productivity. Built surfaces in cities are composed of a high percentage of non-reflective and water-resistant construction materials, which coupled with the lack of vegetation and moisture-trapping soils – that provide shade and contribute to cooling the air – means that temperatures in cities tend to be higher than those of surrounding areas. The difference between temperatures in cities as compared to rural areas is known as the urban heat island effect (Oke, 1997). What is more, because cities concentrate people and productive activity, productivity losses here can have amplified effects. As the number of people living in cities continues to increase,<sup>1</sup> so does the potential for adverse effects of increasing temperatures, in the absence of adaptation.

Research on the effects of heat waves in terms of labour productivity in the specific context of cities is still relatively scarce.<sup>2</sup> In order for policy makers to implement measures to adapt to heat waves in cities a better understanding of the scale of damages and the effectiveness of different adaptation strategies is required.

We use our methodology to assess the impact of heat to the urban economy through decreased labour productivity, as well as to compare the effectiveness of different adaptation measures. Our model starts from the micro-level evidence that heat induces a decrease in productivity at the individual level and shows how this decrease aggregates into production losses at the macro/city level.

We first estimate hourly productivity loss functions for individual workers at different levels of work intensity based on ISO standards for recommended hourly work rates at different levels of Wet Bulb Globe Temperature (WBGT). Work intensities are then attributed to different sectors of the metropolitan economy depending on the amount of energy necessary to perform different activities.

We then define constant elasticity of substitution (CES) production functions for each sector that specifically encompass the productivity loss functions. The production functions are calibrated with economic data and aggregated at the city level according to specific weights given to each sector. This approach allows us to assess various characteristics of urban production, including the flexibility of the productive system in terms of the degree of substitutability between labour and capital, its labour intensity, and the relative importance of different sectors in the economy.

Finally, we use the UrbClim model (De Ridder *et al.*, 2015; De Ridder *et al.*, 2014 – D4.1) to project outdoor city level temperatures for the year 2005 and the periods 2026-2045 and 2081-2100, which is subsequently used to compute indoor climatic conditions in an example office building by the EnergyPlus model. We use this in order to compute an estimate of future production costs in three case study cities: Antwerp, Bilbao, and London.

As well as benchmarking the damage costs of heat waves on the urban economy, we also use the economic cost methodology to examine the averted losses of different adaptation measures, including behavioural change, increased mechanical ventilation, the use of solar blinds, increased insulation, and air conditioning. Furthermore, we

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<sup>1</sup> The urban population is expected to grow by 1 billion people in less developed countries and by 70 million people in developed countries by 2030 (UN DESA, 2014).

<sup>2</sup> An exception is Sabbag (2013), who explores the literature on the effect of heat waves applying conclusions applied to urban settings.

examine the energy demand of air conditioning as an example of analysing benefits and costs of adaptation measures. The results of the energy demand analysis show that the economic cost methodology is a relatively simple and promising method for examining benefits and costs.

In another RAMSES deliverable, D1.3, further data will be generated on the installation costs of heat adaptation measures such as air conditioning, mechanical ventilation, solar blinds and insulation, as well as flooding adaptation measures such as green roofs and permeable paving. While it would have been interesting to factor in and compare the costs of other adaptation measures, disaggregated data of sufficient quality were not available. This is partly because data of sufficient quality were not found in the academic literature and partly due to the substantial delay in adaptation cost data as part of RAMSES deliverable D1.3 following the departure of one of the partners from the consortium.

### ***2.3 Model-generated economic costs – the case of heat and productivity***

The results of the methodology show that costs of heat waves to the urban economy are highly variable and depend on characteristics of production, such as the elasticity of substitution between capital and labour, and the sectoral division of production. For example, based on the assumptions set out in this report, we estimate that in a warm year in the far future (2081-2100) the total losses to the urban economy could be between 0.4% (London) and 9.5% (Bilbao) of GVA, in the absence of adaptation. This implies substantial potential costs of heat through labour productivity losses, even when we consider only cities in relatively cool countries. Additionally, we find that behavioural adaptation in the form of changing working hours generates diverse results in different cities, with the most efficient working regime estimated to save up to 0.8% of GVA in Bilbao in a warm year in the near future (2026-2045).

### ***2.4 Other model-generated economic costs***

We extend the economic cost methodology to estimate the costs of heat on the urban economy. We explore the impact of high temperature rail buckling on transport delays in London, and the resulting impacts on economic production in the city under productivity losses. The choice to study this impact was determined by data availability from other RAMSES partners. We also examine the economic cost methodology for pluvial flooding events in London, and their impact on transport delays.

### ***2.5 Other economic costs***

In addition to the data generated by the economic cost methodology for worker productivity losses, high temperature rail buckling and impacts of pluvial flooding on transport delays, we also examine economic results from other work packages, which have been uploaded to the RAMSES Common Platform for linking with the European Clearinghouse, ClimateAdapt. These include direct health costs of heat waves in WP6, which are complementary with our productivity analysis, and can easily be

incorporated to derive comprehensive estimates. We also present results of sea damages for the three case study cities from WP1.

## ***2.6 Structure of this report***

The report is organized into seven major parts. Following the Executive Summary and Introduction, Part 3 “Heat and productivity costs – a transferable method for the city economy” describes the methodology for assessing costs of climate change to the urban economy in detail, using heat and productivity as an example. It also sets out the results of the analysis for the three core case study cities, London, Antwerp and Bilbao, and discusses the results in the context of the methodology.

Part 4 “Other economic costs of heat in cities” presents analyses of heat-related costs through different channels. First, we estimate costs through transport disruptions using the methodology set out in Part 3. Second, we present health costs of heat waves, drawing on research in WP6.

Part 5 “Economic costs of flooding in cities” presents analyses of flooding costs by first estimating their impact through transport disruption again using the cost methodology in Part 3, and second by assessing the costs of sea level rise and costs and benefits of sea protection, drawing on research in WP1.

Part 6 “Data for the RAMSES common platform” sets out the data results that have been uploaded to the RAMSES common platform and will be linked to the European Clearinghouse ClimateAdapt (<http://climate-adapt.eea.europa.eu/>).

Finally, Part 7 sets out the “Conclusions and implications for future research”.

## 3 Heat and productivity costs – a transferable method for the city economy

### 3.1 Urban heat and the cost methodology

We develop a method to estimate impacts of climate change to the city economy through various channels that affect economic production. For example, heat waves may affect the amount of labour supplied by increasing travelling times, or decrease labour productivity, among others. Floods may also decrease the labour supply due to transport disruptions, increase transport costs for inputs or final products, or decrease the amount of capital available for production.

Here we focus on the impact of heat to the urban economy through decreased labour productivity, and use our model to identify vulnerabilities of the city economy and to compare the effectiveness of different adaptation measures. The cost methodology starts from the observation that heat, through its physiological impact on individuals (Kjellstrom *et al.* 2009), induces a decrease in productivity at the individual level and shows how this decrease aggregates into production losses at the city level, for different levels of heat stress. The purpose is to illustrate the use of the methodology, rather than to provide precise estimates.

#### 3.1.1 Climate models at the city level

Since our purpose is to estimate the impact of heat stress in the urban economy, it is important to include the influence of urban built-up areas on the large-scale meteorological data. Hence the use of meteorological (reanalysis) data or rural measurement would be inappropriate in this context. Instead we model the urban influence on hourly air temperatures, land surface temperatures, wind speeds and humidity values using the UrbClim model.

UrbClim is an urban climate model designed to model and study the urban climate at a spatial resolution of a few hundred meters. The model scales large-scale weather conditions down to agglomeration-scale and computes the impact of urban development on the most important weather parameters. It is composed of a land surface scheme describing the physics of energy and water exchange between the soil and the atmosphere in the city, coupled to a 3d boundary layer module, which models the atmospheric dynamics above the urban agglomeration.

The atmospheric conditions far away from the city centre are fixed by meteorological input data, while local terrain and surface data influences the heat fluxes and evaporation within the urban boundaries. The terrain input of UrbClim consists of the spatial distribution of land use types, the degree of covering of the soil by artificial structures such as buildings and roads, and the vegetation cover fraction, all taken from publicly available remote-sensing data sets. A detailed description of the model is provided in De Ridder, *et al.* (2014) (Deliverable 4.1) and in De Ridder *et al.* (2015), and the set-up for this study is provided in Hooyberghs *et al.* (2014) (Deliverable 4.2) and Lauwaet *et al.* (2015). Validation campaigns have compared air temperatures (De Ridder *et al.*, 2015, Lauwaet *et al.*, 2015, De Ridder, *et al.*, 2014 – Deliverable 4.1 –, and De Ridder *et al.*, 2011), wind speeds (Hooyberghs *et al.*, 2014 – Deliverable 4.2)

and land surface temperatures (Zhou, et al 2015) of UrbClim with measurements and remote sensing data a lot of cities.

The current climate is studied by coupling UrbClim to large-scale meteorological data of the European Centre for Medium-Range Weather Forecasts (ECMWF); within the current study we use the ERA-Interim reanalysis data. 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 IPCC (IPCC, 2013). The IPCC report 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 computational time limitations, we consider only the RCP8.5 scenario. Although this is the scenario with the largest warming potential, it still assumes emissions well below what the current energy mix would produce in the future (Peters *et al.* 2013).

The details of the coupling between UrbClim and GCM-output are described in Lauwaet *et al.* (2015) and Hooyberghs *et al.* (2015) (Deliverable 4.2). In order to reduce computational time, we only couple UrbClim to the output of one GCM, the GFDL-ESM2M model of NOAA (Dunne, 2012 and Dunne, 2013). This model was selected since, among the 11 GCMs that are considered in Hooyberghs *et al.* (2015) (Deliverable 4.2), it yields the median warming of the mean temperature for the three cities under investigation.

The ERA-interim runs described above are considered as the benchmark for all future climate projections. Therefore, we introduce a bias correction which reduces the differences between (1) the urban climate simulated with ERA-interim meteorological input, and (2) the urban climate simulated with the GCM as a driver, for the reference period. The bias correction rescales the mean and the standard deviation of the GCM-runs to the ones for the ECMWF runs. A more detailed description of the coupling between UrbClim and the GCMs and the associated bias correction is provided in Lauwaet *et al.* (2015) and Hooyberghs *et al.* (2015) (Deliverable 4.2).

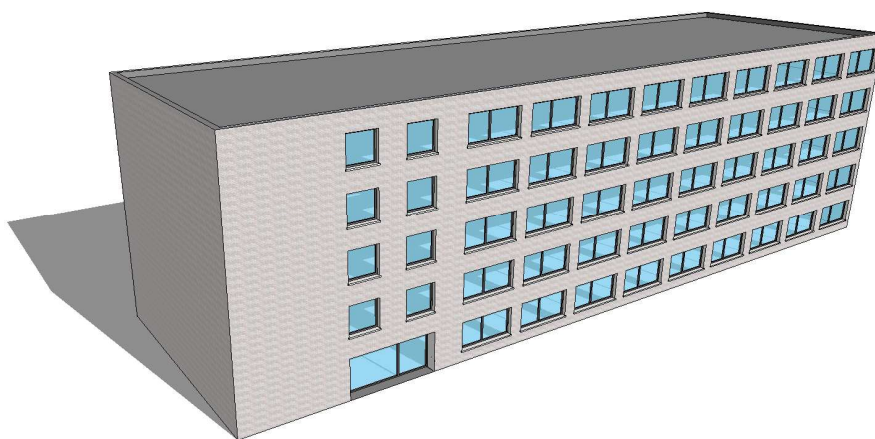
### 3.1.2 Estimating indoor temperature and working conditions

This study focusses on office buildings, either equipped with a cooling system either ‘free-running’ during summer time, i.e., without active cooling equipment. The case study model under investigation is a typical modern 5-storey office building. The generic typology can be considered representative for contemporary building praxis, and is identical for the three case study locations considered. While the aim for future research is to model different types of buildings (e.g. warehouses, factories) that are relevant to different sectors of the economy, the large computational time pertaining to buildings simulations on a climatological scale hinders such an analysis at this time. We therefore restrict the analysis to one prototype building. This is one of many caveats that need to be recognised when interpreting any economic cost outputs from the methodology.

We study two versions of the prototype building, which only differ in the presence or absence of a cooling system, but are otherwise identical. For the former building, the focus lies on the energy demand of the heating, ventilation, and air conditioning (HVAC) system, while for the latter one, the focus lies on productivity losses.

Indoor thermal comfort and energy use of a building are heavily influenced by the outdoor thermal environment. The thermal conduction through the building skin and heat transport by air exchange depend on the thermal gradient between indoor and outdoor air temperature.<sup>3</sup> Other local climatic conditions such as wind speeds and directions, sky coverage and outdoor air humidity will also have an influence on the energy flows to and from building. It is thus expected that the combined effect of climate change and urban heat island effect will result in impacts on the indoor ambient temperatures of buildings, especially during summer.

*Figure 3-1 Rendered image of the case study office building*



The results reported refer to the third storey 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 through the floor and ceiling of this storey, which allows the floors and ceilings to be modelled with adiabatic boundary conditions. Due to the elevated location, shadowing effects of parking lots, small trees, etc. can be neglected. It is assumed that the building receives no shadow from surrounding buildings or larger trees. The building has a heavy weight construction comprising concrete floors and masonry external walls with 10 cm rigid polyurethane foam insulation board in the cavity (Lambda-value  $\lambda = 0.0245$  W/mK).

*Table 3-1 Main characteristics of the building envelope of the 3th storey*

Construction	Surface	Thermal properties
External facade	530.40 m <sup>2</sup>	U-value = 0.201 W/m <sup>2</sup> K

<sup>3</sup> For details see also Olonscheck et al. (2011) and Olonscheck . (2015).

Windows	152.96 m <sup>2</sup> (136 m <sup>2</sup> glass, 16.96m <sup>2</sup> frame)	U <sub>glass</sub> =1.199W/m <sup>2</sup> K U <sub>frame</sub> =1.199W/m <sup>2</sup> K SHGC <sub>glass</sub> =0.389
Floor (Ceiling)	1080m <sup>2</sup>	(adiabatic)

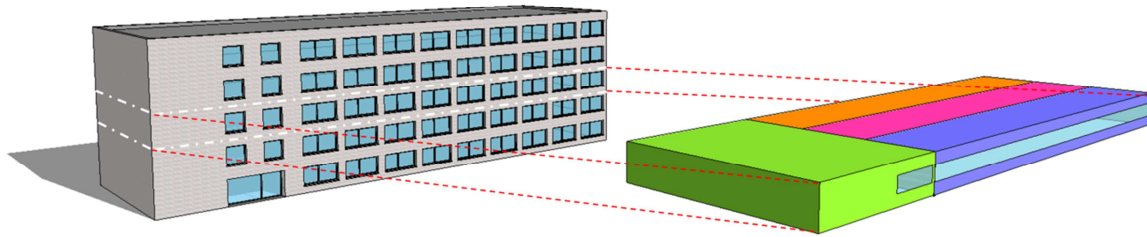
The impact of changes in outdoor climate on the performance of the building is evaluated through computer-aided simulations. A dynamic building performance simulation software is an engineering tool which can predict the energy performance of a building by calculating envelope heat gains and space heat loads, system and plant operation. (Boyano *et al.*, 2013; Crawley *et al.*, 2008 ; Hong *et al.*, 2000). These models use a forward engineering approach rather than statistical methods or calibration; in this approach the equations describing the physical behaviour of systems and their inputs are known and the objective is to predict the output. (Fumo, 2014)

By modelling the physical properties and governing heat flow equations, the tool can accurately assess the temperature profile, the perceived thermal comfort and the energy demand of the building. (Ryan *et al.*, 2012; Loutzenhiser *et al.*, 2009). In this study, the building is modelled using the open source EnergyPlus simulation software (v8.2.0, released September 2014), a state-of-the art building energy analysis software which is managed by USA National Renewable Energy Laboratory (NREL (Crawley *et al.*, 2001; Henninger *et al.*, 2004).

The 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, each having 61.20m<sup>2</sup> glass area oriented either North or 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 and contains 13.6m<sup>2</sup> outdoor windows, evenly distributed amongst Northern and Southern façade. The four thermal zones all have an identical floor area of 270m<sup>2</sup>.

The air infiltration is set to 0.4 m<sup>3</sup>/h per square metre of external facades. The ventilation rate for the three office spaces is assumed to be 5 m<sup>3</sup>/h/m<sup>2</sup> during occupied hours, and 0 m<sup>3</sup>/h/m<sup>2</sup> when not occupied in the base case. Considering 10 m<sup>2</sup> of office space available per worker, the ventilation rate equals 50 m<sup>3</sup>/h/person, which corresponds to IDA class 2: “Medium indoor air quality” according to European standards (EN 13779:2007).

*Figure 3-2 Graphical representation of a thermal model representing the third floor which consists of 4 interconnected thermal zones.*



EnergyPlus simulates the heat balance within each of the zones at a user-specified time step, in this case a 10 minute interval. The heat gains and losses through the building enclosure, internal gains, and heat flows due to ventilation, interzone air flows and air infiltration are modelled. By using a small time step transient effects of the construction thermal inertia are also considered (Aste *et al.*, 2015). The internal thermal gains result from 10 W/m<sup>2</sup> artificial lighting installed in the office zones, 7.5 W/m<sup>2</sup> heat loads from the office equipment, and the metabolic heat gains from the workers present. Every person is assumed to have 10 m<sup>2</sup> of office space available, resulting in 27 people present in each of the three office zones when fully occupied.

The thermal loads resulting from the heat balance are passed on to EnergyPlus's integrated systems simulation module, which calculates the corresponding heating and cooling system response, taking into account efficiencies and maximum output power (Crawley *et al.*, 2008). If the system cannot meet the imposed load, or if a cooling system is absent, an imbalance in the heat flows to and from a thermal zone will result in a temperature change. The integrated building and system simulation modules implemented in EnergyPlus thus allow to accurately model the indoor thermal conditions of the building.

### *3.1.3 Productivity loss functions*

The link between heat stress and labour productivity has been extensively studied at the micro level. Studies have found that human performance, both physical and intellectual, varies with temperature, decreasing as heat increases above a certain threshold. Here we benchmark the reduction of worker productivity in the absence of corrective measures (adaptation), and then evaluate the averted productivity losses (adaptation benefits) under a range of adaptation measures.

Early studies showed that cognitive performance in tasks such as vigilance, reaction time, and time estimation decrease with high temperatures (Grether 1973). Similarly, Wyon (1974) showed the negative impacts of moderately high temperatures on type-writing, while Ramsey (1995) demonstrated that increases in temperature lead to



reduced performance in perceptual motor tasks.<sup>4</sup> Since office workers rely strongly on comfortable conditions to perform their daily jobs, the productivity of employees decreases rapidly when indoor temperature or humidity levels rise above certain thresholds (Berger, 2014).

To estimate the reduction in productivity of individual workers due to physiological impacts on workers, a detailed physiological study is required under controlled conditions. However, at the scale of the city, where conditions vary from building to building and street to street, an estimation of physiological changes is not possible. Instead, we follow previous researchers working at the population level by using internationally agreed standards for the length of work breaks at different temperatures above a heat stress threshold (e.g. Kjellstrom *et al.* 2009; Jay and Kenny 2010).

We define worker productivity as the proportion of a working day that a worker can perform a job under different heat conditions (Kjellstrom, 2000). At a comfortable temperature and humidity (estimated using Wet Bulb Globe Temperature, WBGT), worker productivity is defined as 1 (or 100%), with no additional rest time required due to heat. If 25% rest time is required, worker productivity is 0.75 (75%) and so on. Using this approach, we can estimate continuous productivity loss functions based on WBGT levels for every hour of the day. Section 3.2.1 provides more details on the estimation of these loss functions.

A range of international and national standards provide guidelines and regulations for employers to protect employees from heat stress, based on physiological experiments. Here, we use ISO standards as the recognised international benchmark. We then test the robustness of results by comparing the ISO standards with the most accepted US standard provided by the National Institute for Occupational Safety and Health (NIOSH).

Finally, different types of work activity require different energy expenditure and so are affected by heat stress to a greater or lesser extent. Consequently, we derive a productivity loss function for each sector of the economy, based on an estimate of the average work intensity (WI) required for work in that sector.

Many indices exist to measure heat exposure. Of these, one of the most commonly used in occupational health is the Wet Bulb Globe Temperature (WBGT).<sup>5</sup> The WBGT is a combination of three measurements: the natural wet bulb temperature ( $T_{nwb}$ , measured with a wetted thermometer exposed to the wind and heat radiation at the site), the black globe temperature ( $T_g$ , measured inside a 150 mm diameter black globe) and the air temperature ( $T_a$ , measured with a normal thermometer shaded from direct heat radiation). For indoor settings, direct solar radiation is unimportant. Hence the formula  $WBGT = 0.7 T_{nwb} + 0.3 T_a$  is used for indoor WBGT, while for outdoors  $WBGT = 0.7 T_{nwb} + 0.2 T_g + 0.2 T_a$  is used (NIOSH, 1986).

Physiologically, the wet bulb thermometer models the cooling of the body by sweating. To obtain indoor WBGT-values this quantity is combined with the air temperature, while for outdoor situations the incoming radiation is also taken into account. Multiple methods exist to estimate the WBGT from standard meteorological variables, an

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<sup>4</sup> For a review of the literature studying the effects of heat on cognitive performance refer to Hancock and Vasmatazidis (2003).

<sup>5</sup> The WBGT is a composite index used to estimate the effect of temperature, humidity, wind speed and (direct and thermal) radiation on humans introduced by the US army decades ago (Yaglou, 1956).

overview of which is provided in (Lemke, 2012). Following their suggestion, the semi-empirical formula of Bernard (1999) and the thermodynamic model of Liljegren *et al.* (2008) are selected to calculate respectively the outdoor and indoor WBGT.

The productivity of labour for labour of a given work intensity is thus a monotonically non-increasing function of the Wet Bulb Globe Temperature between an upper and a lower bound. Above the upper WBGT bound, worker productivity is zero, while below the lower bound, productivity is 1. Hourly productivity loss from WBGT, for a given work intensity (WI) is given by

$$P_{WI} = \begin{cases} 1 & \text{WBGT} < \text{Min} \\ f(\text{WBGT}) & \text{Min} \leq \text{WBGT} \leq \text{Max} \\ 0 & \text{WBGT} > \text{Max} \end{cases} \quad (1)$$

where  $f(\text{WBGT})$  is a monotonically decreasing function of WBGT. These  $P_{WI}$  functions are then aggregated into annual productivity loss. Productivity loss for labour ( $L$ ) in a given sector  $s$ ,  $a_{L,s}$ , is a function of WBGT through its effect on hourly productivity loss across all working hours ( $h$ ) and working regimes  $\{1, \dots, H\}$ , that is,  $a_{L,s} = \sum_h \sum_{WI=1}^N P_{WI,h}(\text{WBGT})$ .

### 3.1.4 Production function

We define constant elasticity of substitution (CES) production functions for each sector  $s$  of the economy that specifically encompass the productivity loss functions. The CES function is a general form production function that assumes a constant percentage change in factor proportions from a percentage change in the marginal rate of technical substitution. We use the standard form (Arrow *et al.*, 1960). Sectorial production in a given time period  $t$  is thus the result of a certain level of the inputs capital ( $K$ ) and labour ( $L$ ) in the following manner:

$$Y_{c,s,t} = f(L_{c,s,t}, K_{c,s,t}) = A_{s,c} [\theta_s (a_{K,s} K_{c,s,t})^{\gamma_s} + (1 - \theta_s) (a_{L,s} L_{c,s,t})^{\gamma_s}]^{\frac{1}{\gamma_s}} \quad (2)$$

where  $Y_{c,s,t}$  is a measure of production in sector  $s$  in city  $c$  at year  $t$ ,  $A_{s,c}$  is total factor productivity by sector and city,  $\theta_s$  is the share of capital in sector  $s$ ,  $\gamma_s$  measures the degree of substitution between production factors and  $a_{K,s}$  and  $a_{L,s}$  are, respectively, the productivity of capital and labour in sector  $s$ . For simplicity we normalise  $a_{K,s}$  to 1, and  $a_{L,s}$  is the function of WBGT defined in Section 2.2. The elasticity of substitution in each sector  $s$  is given by  $\rho_s = \frac{1}{(1-\gamma_s)}$ .

City production is a sum of sectorial production across all the  $N$  sectors of the urban economy, and given by:

$$Y_{c,t} = \sum_{s=1}^N Y_{c,s,t} \quad (3)$$

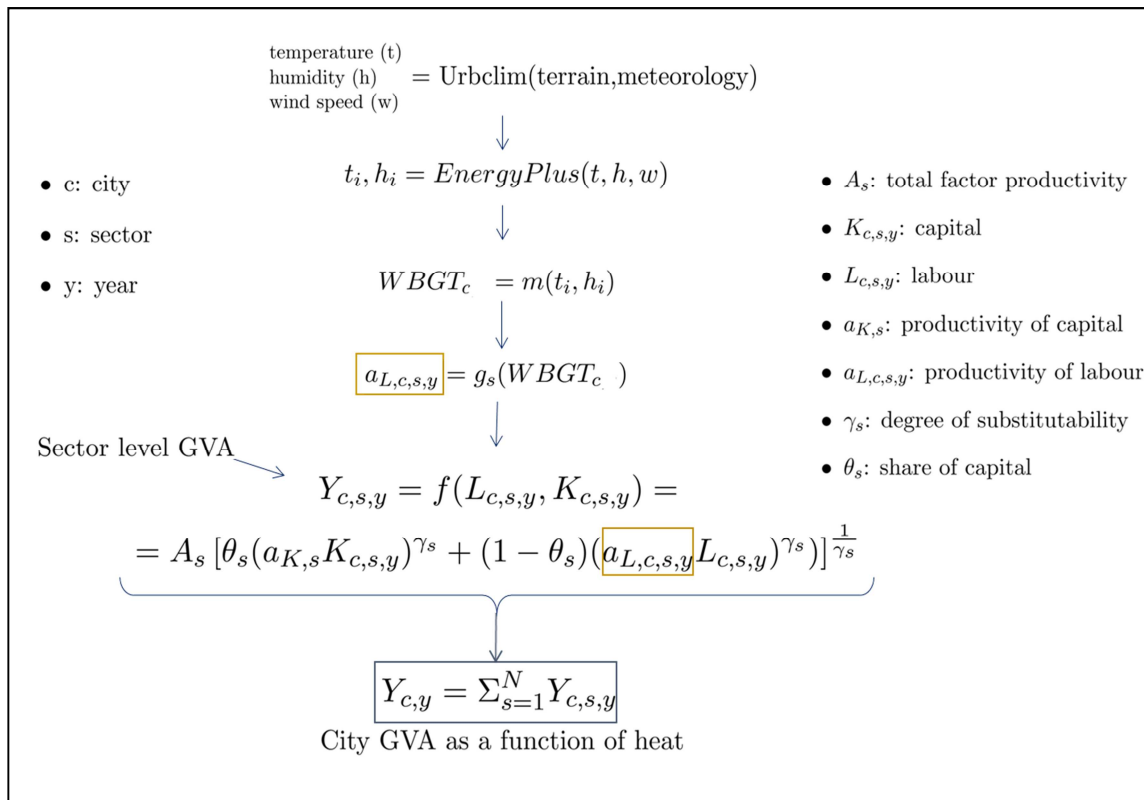
Thus equation (2) can be rewritten as:

$$Y_{c,t} = \sum_{s=1}^N A_{s,c} [\theta_s (a_{K,s} K_{c,s,t})^{\gamma_s} + (1 - \theta_s) (a_{L,s} (\text{WBGT}_h) L_{c,s,t})^{\gamma_s}]^{\frac{1}{\gamma_s}} \quad (4)$$

which gives us city production as a function of WBGT. Because  $a_{L,s}(WBGT)$  is a decreasing function of WBGT, and WBGT is increasing in temperature, city production is by construction a decreasing function of workplace temperature. Exactly how production varies with WBGT depends both on weight of each sector on total production, as well as on the parameters of each sector's production function.

Hence the use of an explicit production function for each sector that is aggregated into city Gross Value Added (GVA) enriches the analysis, as it allows us to track the impact of different economic structures on the final effect of heat stress on the urban economy. An overview of the full model, from the physical modelling to the final function of city GVA, is presented in Figure 3-3.

Figure 3-3 Model Overview



### 3.2 Calibration

We calibrate the model to the economies of Antwerp (Belgium), Bilbao (Spain), and London (United Kingdom). Productivity losses and cooling costs are computed for three periods of twenty years: a reference period (1986 – 2005), and a near (2026 – 2045) and far (2081 – 2100) future period. To reduce the computational costs, only one reference year and 4 future years are considered in the economic analysis. We use the year 2005 as the reference year, and for each future period (2026-2045 and 2081-2100) and for each city, we choose a “cool” year (the year with the minimal productivity loss) and a “warm” year (the year with the maximal productivity loss). The choice of the years is

dependent on not only the exact time frames but also the choice of the global climate model, but by considering a warm and a cool year, this procedure defines a range for presenting climate projection results. The chosen years are listed in Table 3-2.

*Table 3-2 Future years used in the analysis*

	<b>Antwerp</b>	<b>London</b>	<b>Bilbao</b>
<b>Near future cool</b>	2038	2043	2028
<b>Near future warm</b>	2044	2042	2040
<b>Far future cool</b>	2097	2097	2092
<b>Far future warm</b>	2084	2083	2099

We use the statistical classification of economic activities in the European Community (abbreviated as NACE) to classify economic activities into sectors. This gives us a total of seven broad sectors. Their full names, along with the reduced name used in the remainder of the paper, are set out in Table 3-3.

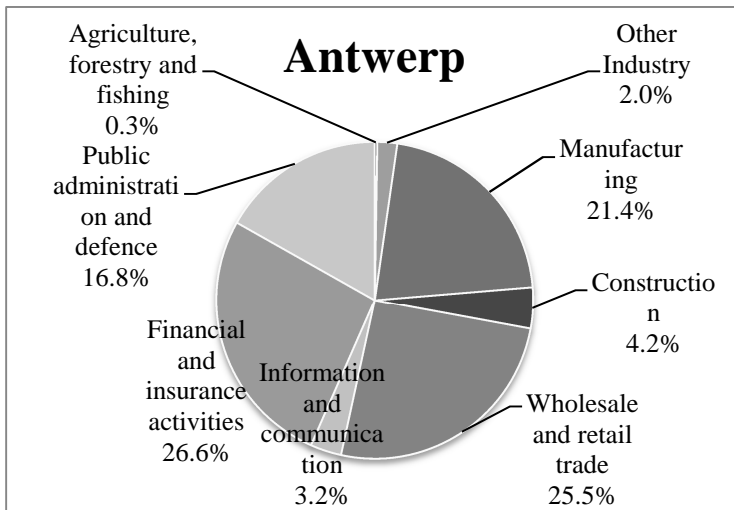
*Table 3-3 List of Economic Sectors Used*

<b>Full Sector Name</b>	<b>Reduced Name</b>
Agriculture, forestry and fishing	Agriculture, forestry and fishing
Industry (except construction & manufacturing)	Other Industry
Manufacturing	Manufacturing
Construction	Construction
Wholesale and retail trade, transport, accommodation and food service activities	Wholesale and retail trade
Information and communication	Information and communication
Financial and insurance activities; real estate activities; professional, scientific and technical activities; administrative and support service activities	Financial and insurance activities
Public administration and defence; compulsory social security; education; human health and social work activities; arts, entertainment and recreation activities	Public administration and defence

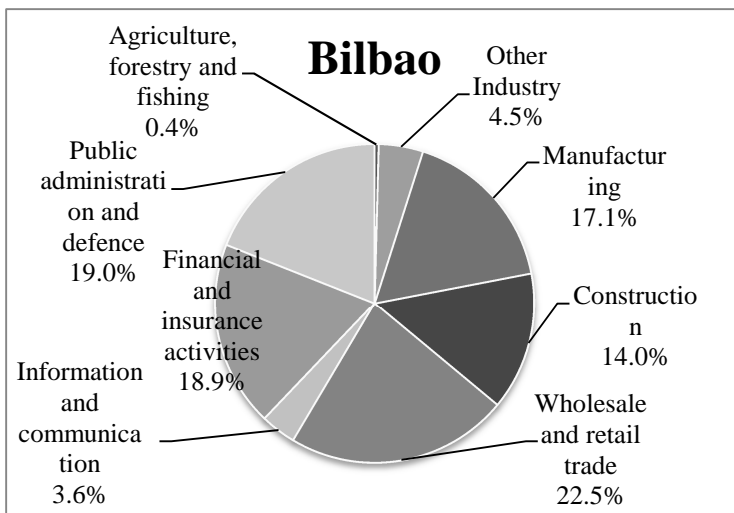
To measure production we use Gross Value Added (GVA) at the sector level. GVA measures the value of goods and services produced in each sector of the economy minus intermediate consumption.

The sectoral divides and total GVA for the reference period for each of the cities are presented in Figure 3-4. The total GVA varies from €25983 million in Bilbao to €471647 million in London. The distribution of GVA between sectors also varies considerably. For example, the manufacturing sector account for 21.4% of the GVA of Antwerp but only 5.7% of that of London.

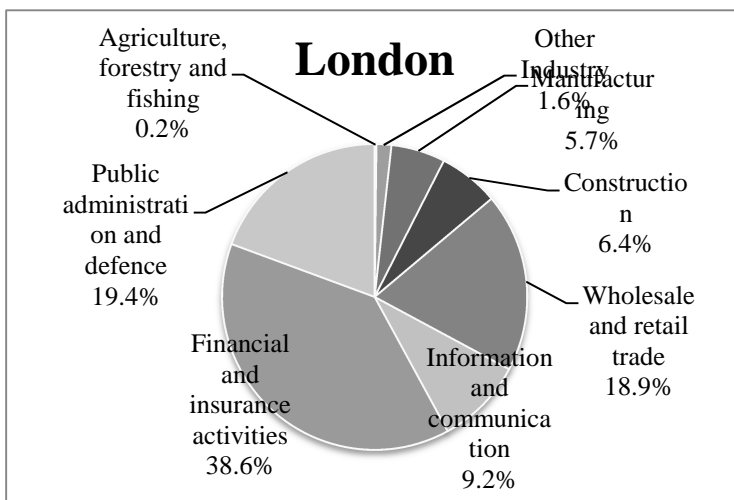
Figure 3-4 GVA of Antwerp, Bilbao and London (2005)



Total GVA:  
€31798.9 million



Total GVA:  
€25982.7 million



Total GVA:  
€ 471646.8 million

### 3.2.1 Calibrating productivity losses

As an international standard, we use ISO standard 7243:1989 on heat stress at different work intensities to estimate worker productivity loss functions (ISO 1989). Following Kjellstrom *et al.* (2009), we estimate the WBGT at which the ISO recommends an average, acclimatised worker should perform work at 100%, 75%, 50% and 25% productivity, as well as the threshold WBGT above which workers are performing at or very close to zero capacity. Using the method set out by Kjellstrom *et al.* (2009) we estimate the WBGT for each work intensity and for each work/rest ratio from the graphic: the results are shown in Table 3-4.

Table 3-4 Worker productivity at different work intensities, using ISO standards for an average acclimatised worker wearing light clothing (ISO 7243)

Worker productivity (per hour)	Light work (WI = 180W) WBGT (°C)	Moderate work (WI = 295W) WBGT (°C)	Heavy work (WI = 415W) WBGT (°C)
100% (full work)	31.0	28.6	26.8
75%	31.5	29.0	27.8
50%	32.0	30.5	29.5
25%	32.5	31.7	31.2

Using the estimations in Table 3-4, productivity loss functions for five different work intensities (WI) were calculated. The functions, set out below, are also shown in Figure 3-5 Hourly worker productivity loss functions based on ISO standards

Work intensity 1 ( $WI_1 = 180W$ ):

$$P_1 = \begin{cases} 1 & WBGT < 31 \\ 16.5 - 0.5WBGT & 31 \leq WBGT \leq 33 \\ 0 & WBGT > 33 \end{cases}$$

Work intensity 2 ( $WI_2 = 240W$ ):

$$P_2 = \begin{cases} 1 & WBGT < 29.6 \\ 10.1 - 0.3WBGT & 29.6 \leq WBGT \leq 32.9 \\ 0 & WBGT > 32.9 \end{cases}$$

Work intensity 3 ( $WI_3 = 295W$ ):

$$P_3 = \begin{cases} 1 & WBGT < 28.3 \\ 7.20 - 0.2WBGT & 28.3 \leq WBGT \leq 32.8 \\ 0 & WBGT > 32.8 \end{cases}$$

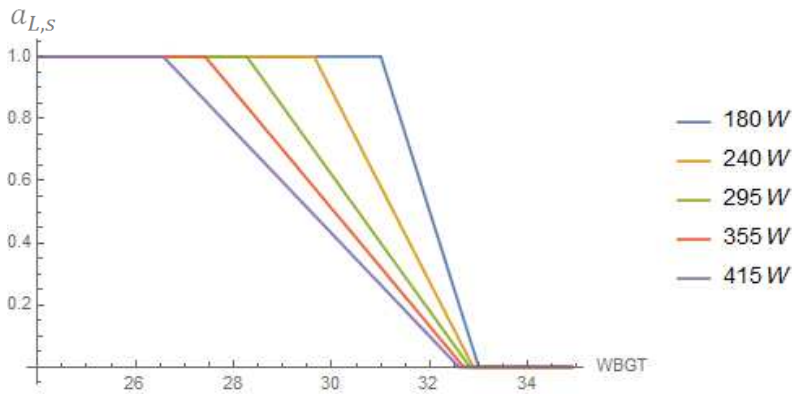
Work intensity 4 ( $WI_4 = 355W$ ):

$$P_4 = \begin{cases} 1 & WBGT < 27.4 \\ 6.2 - 0.2WBGT & 27.4 \leq WBGT \leq 32.7 \\ 0 & WBGT > 32.7 \end{cases}$$

Work intensity 5 ( $WI_5 = 415W$ ):

$$P_5 = \begin{cases} 1 & WBGT < 26.6 \\ 5.4 - 0.2WBGT & 26.6 \leq WBGT \leq 32.6 \\ 0 & WBGT > 32.5 \end{cases}$$

Figure 3-5 Hourly worker productivity loss functions based on ISO standards



The productivity loss functions for work intensities  $WI_1$  (180W),  $WI_3$  (295W) and  $WI_5$  (415W) were calculated directly from Table 3-4. In addition, we estimated functions for  $WI_2$  (240W) and  $WI_4$  (355W) by taking the mean average of the other loss functions. This provided a set of loss functions, each of which can be allocated to a specific sector of the economy.

We tested the robustness of results based on the ISO standards by comparing them with the US national standard provided by the National Institute for Occupational Safety and Health (NIOSH). The WBGT for each work intensity is shown in Table 3-5. In both the ISO and NIOSH cases, workers are assumed to be acclimatised. This provides a relatively conservative estimate of heat stress impacts on individual productivity. However, non-acclimatised loss functions can also be used, for example based on estimates provided by NIOSH (see Table 3-6).

Table 3-5 Worker productivity at different work intensities, using US standards for acclimatised workers (NIOSH)

Worker productivity (per hour)	Light work ( $WI = 180W$ )	Moderate work ( $WI = 295W$ )	Heavy work ( $WI = 415W$ )
	WBGT (°C)	WBGT (°C)	WBGT (°C)
100% (full work)	29.5	27.5	26.0
75%	30.5	28.5	27.5
50%	31.5	29.5	28.5
25%	32.5	31.0	30.0

Table 3-6 Worker productivity at different work intensities, using US standards for non-acclimatised workers (NIOSH)

Worker productivity (per hour)	Light work (WI = 180W) WBGT (°C)	Moderate work (WI = 295W) WBGT (°C)	Heavy work (WI = 415W) WBGT (°C)
100% (full work)	27.5	25.0	22.5
75%	29.0	26.5	26.5
50%	30.0	28.0	28.0
25%	31.0	29.0	29.0

To allocate an appropriate productivity loss function to each sector, we used the classification of different job activities by work intensity used by the British and European standard on heat stress, BS EN 27243:1994, and based on the ISO 7243:1989 (see British Standards Institution 1994). Table 3-7 summarizes the resulting relationship between work intensity and sector.

Table 3-7 Estimated work intensity in different sectors of the economy

Sector	Average Work Intensity (W)	Work Intensity Category (WI)
Agriculture, forestry and fishing	355	Moderate/high (4)
Other Industry	295	Moderate (3)
Manufacturing	240	Light/moderate (2)
Construction	355	Moderate/high (4)
Wholesale and retail trade	240	Light/moderate (2)
Information and communication	180	Light (1)
Financial and insurance activities	180	Light (1)
Public administration and defence	240	Light/moderate (2)

For simplicity, we assume that work in the agricultural and construction sectors are performed outdoors, while work in all other sectors is performed indoors. As a baseline, we assume all individuals work from 9h-13h and 14h-17h, under legal ventilation standards established in Antwerp, without air conditioning.

We also assume that losses to productivity due to heat can potentially occur during the three hottest summer months (not in other months of the year) and that all workers take their holiday during the summer period. As a result, we estimate losses for only 2 out of the 3 months. This is a very conservative estimation as losses are likely to occur in more months throughout the year, especially for the far future. Hence, the end-of-the-century results are actually a lower limit on the true fraction of lost working hours and cooling costs.



### 3.2.2 Substitution of capital and labour

The production function parameters ( $\rho$  and  $\theta$ ) are calibrated at the sector level and some of the choice and outcome variables (namely,  $L$ ,  $A$ , and GVA) are calibrated at city-sector level. The data was retrieved from EUROSTAT's regional statistics for metropolitan regions.<sup>6</sup> Metropolitan regions are NUTS3 regions or a combination of NUTS3 regions which represent all agglomerations of at least 250 000 inhabitants. All variables were calibrated for the year 2005 as the reference year. We choose to use 2005 data instead of introducing another set of strong assumptions that are inevitable to perform economic forecasts for periods in the far future, such as 2081-2100.

The values for the elasticity of substitution ( $\rho$ ) and the proportion of each input ( $\theta$ ) are estimated at the sector level for the United States, for 1997 and 1960-2005, respectively. The estimation of  $\rho$  is taken from Young (2013), and that of  $\theta$  from Valentinyi and Herrendorf (2008). The sectors differ and were approximated to match the NACE. The sectors used, as well as the years estimated are set out in Table 3-8.

Finally, estimates of capital stocks at the city level are not available from EUROSTAT. Accordingly, the Perpetual Inventory Method (PIM) was used to estimate  $K$  from regional-level time series of grossed fixed capital formation (GFCF) also available from EUROSTAT. The PIM is a commonly used approach of measuring capital stocks,<sup>7</sup> based on the idea that they constitute cumulated flows of investment (OECD, 2009). It is based on the assumption that  $I/(g+\delta)$  is the expression for the capital stock in the steady state of the Solow model (Solow, 1956).

We start by computing the initial capital stock as

$$K_0 = \frac{I_0}{g + \delta}$$

Where  $I_0$  is our measure of investment (gross fixed capital formation) in the first year available,  $g$  is the average geometric growth rate for the investment series between the first year with available data and the last, and  $\delta$  is the depreciation rate.

Gross fixed capital formation is defined as the resident producers' acquisitions, less disposals, of fixed assets during a given period plus certain additions to the value of non-produced assets realised by the productive activity of producer or institutional units. It is available from EUROSTAT for London, for the region of Antwerp, and for the Basque Country, where Bilbao is situated, for each of the sectors used in the analysis.

We use the depreciation rate estimated by the UK Office for National Statistics (ONS) for all three cities. The ONS assumes that plant and machinery has a life of 25-30 years in most industries, which is equivalent to a geometric rate of 5%-9% if growth does not exceed 5% per annum, much lower than the US rate. We choose a rate of 7%. Finally, we use the fixed capital investment deflators from Bluenomics ([www.bluenomics.com](http://www.bluenomics.com)), which are defined for each country.

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<sup>6</sup> The sectoral distribution was not available for Bilbao for 2005. We took the closest year for which sectoral GVA was available (2008) to calculate each sector's weight, and used the total 2005 GVA to estimate sectoral GVA in 2005.

<sup>7</sup> Two examples are Hall and Jones (1999) and Caselli (2005).

We then update the values of  $K$  for each year  $t$  to give us 2005 levels of capital according to:

$$K_t = I_t + (1 - \delta)K_{t-1}$$

All the sources of data for the calibration of the production function, along with the sectors used to approximate NACE for each, are described in Table 3-8.

*Table 3-8 Sources and Sectors for Calibration*

	GVA (Y) and Employment (L)	Gross Fixed Capital Formation	Capital/Labour shares ( $\theta$ )	Elasticity ( $\rho$ )
Source	EUROSTAT; Antwerp, Bilbao, London	EUROSTAT; Antwerp, Basque Country, London	Valentinyi and Herrendorf (2008) United States	Young (2013) United States
Years	2005	Varying	1997	1960-2005
Sectors	Agriculture, forestry and fishing	Agriculture, forestry and fishing	Agriculture	Agriculture
	Industry (except construction and manufacturing)	Industry (except construction and manufacturing)	= Manufactured consumption & Equipment & Construction	= Manufacturing & Metal mining, Coal mining, Oil and gas extraction, Non-metallic mining
	Manufacturing	Manufacturing	Manufactured consumption	= Food and Kindred Products, Tobacco, Textile mill products, Apparel, Lumber and wood, Furniture and fixtures, Paper and allied, Printing, publishing and allied, Chemicals, Petroleum and coal products, Rubber and miscellaneous products, Leather, Stone, clay, glass, Primary metal, Fabricated metal, Non-electrical industry, Electrical industry, Motor vehicles, Transportation Equipment and ordinance, Instruments, Miscellaneous Manufacturing
	Construction	Construction	Construction	Construction
	Wholesale and retail trade, transport, accommodation and food service activities	Wholesale and retail trade, transport, accom. and food service activities	= Manufactured consumption & Services	= Transport & Services & Trade
	Information and communication	Information and communication	Services	Construction
	Financial and insurance activities; real estate activities; professional, scientific and technical activities; administrative and support service activities	Financial and insurance activities; real estate activities; professional, scientific and technical activities; administrative and support service activities	Services	Finance, Insurance & Real Estate
	Public administration and defence; compulsory social security; education; human health and social work activities; arts, entertainment	Public admin. and defence; compulsory social security; education; human health and social work activities; arts,	Services	Government Enterprises

	and recreation; other service activities; activities of household and extra-territorial organizations and bodies	entertainment and rec.; other service activities; activities of household and extra-territorial organizations and bodies		

Notes: The = is used to indicate that an average of more than one sector was used.

### 3.2.3 Adaptation measures

We choose the adaptation measures most likely to be effective, based on Floater *et al.* (2014) (Deliverable 5.1) and Kallaos *et al.* (2015) (Deliverable 2.4) and the results of Task 4.3 (to appear in Deliverable 4.3). First, we estimate losses under behavioural adaptation, in the form of changing working hours. We use three regimes where work is delayed towards later in the evening, three where it is done earlier in the morning, and one extreme regime that includes early morning and late afternoon work. The working regimes used are, in 24h format:

- Baseline hours: 9h-13h; 14h-17h
- Afternoon schedules: 9h-13h; 15h-18h & 9h-13h; 16h-19h & 9h-13h; 17h-20h
- Morning schedules: 8h-12h; 14h-17h & 7h-12h; 15h-17h & 6h-13h
- Extreme: 7h-11h; 17h-20h

The hard adaptation measures, on the contrary, mainly deal with decreasing the indoor temperature in the office building. We first estimate the effect of an increase in the rate of mechanical ventilation (from 22m<sup>3</sup>/h/p, the legal minimum in Belgium, to 50m<sup>3</sup>/h/p). In this scenario, the air in the office building is refreshed two times each hour.

We also 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<sup>2</sup>), thereby effectively reducing the incoming solar radiation. Both the external shading and the increased ventilation rates were previously suggested by Jentsch *et al.* (2008).

We also study the effect of an increase in insulation. This means a reduction in the heat transfer through the glazing by decreasing the standard U-value of 1.2W/m<sup>2</sup>/K to 0.8W/m<sup>2</sup>/K.

Finally, we focus on air conditioning by studying the energy necessary to completely eliminate productivity losses for indoor work. Benefit/cost ratios of air conditioning, taking account of averted losses and energy demand costs, are presented in Section 3.3.1.

In addition to studying the impact of these measures on productivity, we study the performance of the different measures in terms of their impact on energy costs. 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<sup>3</sup>/h/p), in order to reduce the ventilation costs. Because of this, the temperature increases and hence higher cooling costs are needed during the day. As an adaptation measure, we propose to keep the ventilation during the night at the same rate as during the day (at 22 m<sup>3</sup>/h/p) and study the impact of this measure in terms of energy costs. This option has already received some attention (Seppanen, 2003; Frank, 2005).

Finally, changing the setpoint temperature of the cooling system provides an additional way to reduce the cooling demand, for instance by increasing the maximally allowed temperature in the building from 25°C to 31°C. This adaptation measure has also received some attention in scientific literature (Li, 2012 and references therein), and in a 2005 field test workers in central government buildings in Japan were asked to increase the summer air-conditioning start-up temperature to 28°C (Roaf, 2010). These measures are summarized in Table 3-9.

*Table 3-9 List of adaptation measures used*

<b>Adaptation measure</b>	<b>Description</b>
Behavioural adaptation	Changing working hours
Increased ventilation	Increase in ventilation from the legal level 22m <sup>3</sup> /h/p to 50m <sup>3</sup> /h/p
Solar blinds	Installing solar blinds on the outside of windows
Insulation	Increase in insulation
Air conditioning	Use of air conditioning
Nightly ventilation	Increased ventilation during the night
Higher setpoint	Increasing the setpoint temperature of the cooling system

### 3.2.4 Energy demand

The energy demand of the HVAC system in a building with a cooling unit consists of two parts – one related to the ventilation and the other to the cooling system. The demand of the cooling system depends on the temperature in the office building, and hence differs hour after hour. The energy consumption of the ventilation scheme is independent of the climatic variables. Hence, for each building set-up, the cost is constant in time. 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 (which keeps the temperature below the setpoint value in all the rooms of the building simultaneously), it is impossible to disentangle the costs for the different rooms. We will therefore always provide ventilation and cooling costs for both north and south facing rooms.

A bias correction is again introduced for the cooling costs to reduce the unwanted difference between the ERA-Interim runs and the reference period runs using GCM climatic data, in the spirit of the bias correction for air temperatures (Lauwaet *et al.*, 2015). This gives us total energy costs in MWh for a room of 1080 m<sup>2</sup> and height 3.4m.

In order to monetize the energy costs we use energy prices and total non-residential floor space in each of the three cities. An approximate estimate of total floor space was collected from government contacts within each city. When available all floor space related to economic activity was used, and when not we used proxy values from retail data.

In terms of energy costs, we use past energy prices. Due to the variability in prices, we use an average of semi-annual data, from 2007 to 2014, available for each country from Bluenomics ([www.bluenomics.com](http://www.bluenomics.com)). We focus on medium size industrial consumers medium standard industrial consumption band with an annual consumption of electricity between 500 and 2000 MWh. Electricity production and network costs including all non-recoverable taxes and levies.

### 3.3 Results

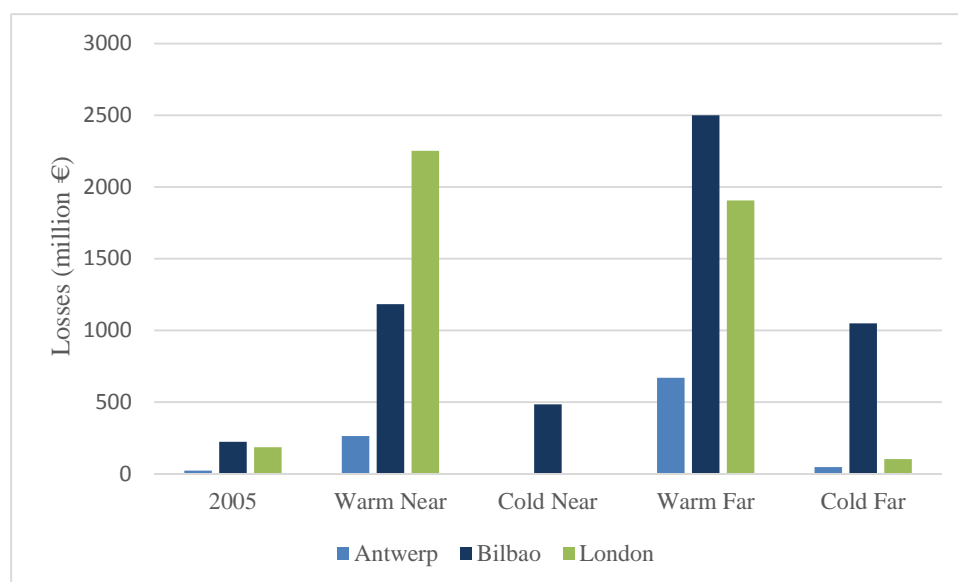
#### 3.3.1 Economic losses in different sectors

Estimated losses due to heat stress and productivity are non-negligible. In a warm year in the far future they are estimated to be of 0.4% of GVA in London, 2.1% in Antwerp, and 9.5% in Bilbao. These correspond to total losses of around €1,900 million for London €669 million in Antwerp, and €2,500 million in Bilbao, in 2005 prices.

Even though the loss to the London economy is substantial, in relative terms it is the lowest. This is due to a combination of lower temperatures and an economic structure that implies less vulnerability to heat stress. This is for example due to the large weight of the financial sector on London's GVA. This sector combines low labour intensity and lower impacts of heat due to lower work intensities.

Losses will tend to increase with time, in particular in warm years, although not always linearly. Figure 3-6 presents losses in the five years for the three cities.

Figure 3-6 Heat related GVA losses across time



Losses vary greatly across sectors. While in Antwerp losses in the manufacturing sector amount to 24% of all losses, in London they are only 6%. On the contrary, the construction sector accounts for only 4% and 6% of losses in Antwerp and Bilbao, respectively, while it accounts for 18% in London.

Figure 3-7 Antwerp: Heat losses in a warm year in the far future

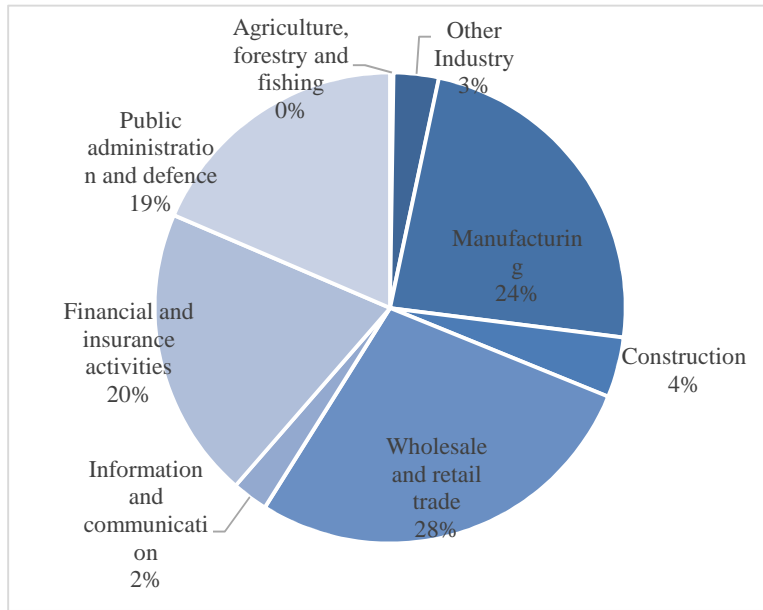


Figure 3-8 Bilbao: Heat losses in a warm year in the far future

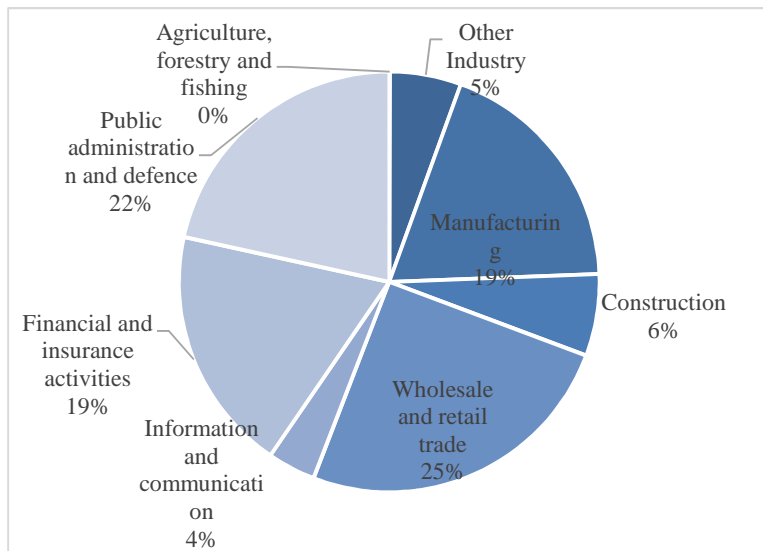
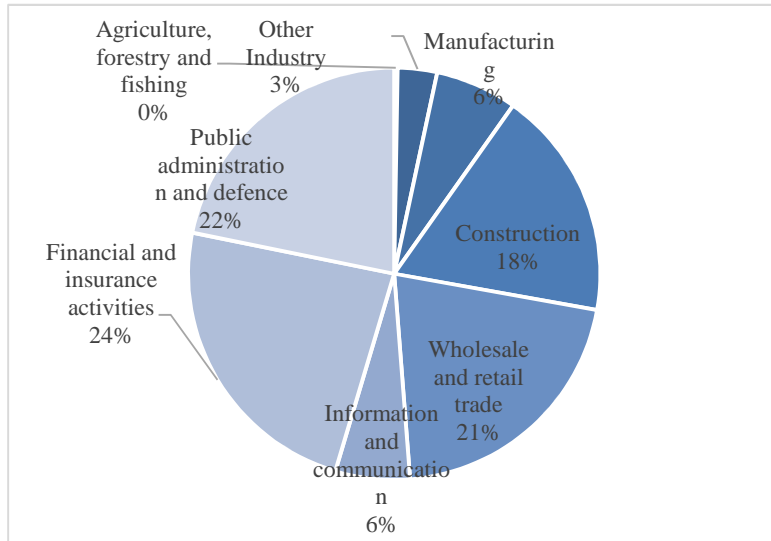


Figure 3-9 London: Heat losses in a warm year in the far future



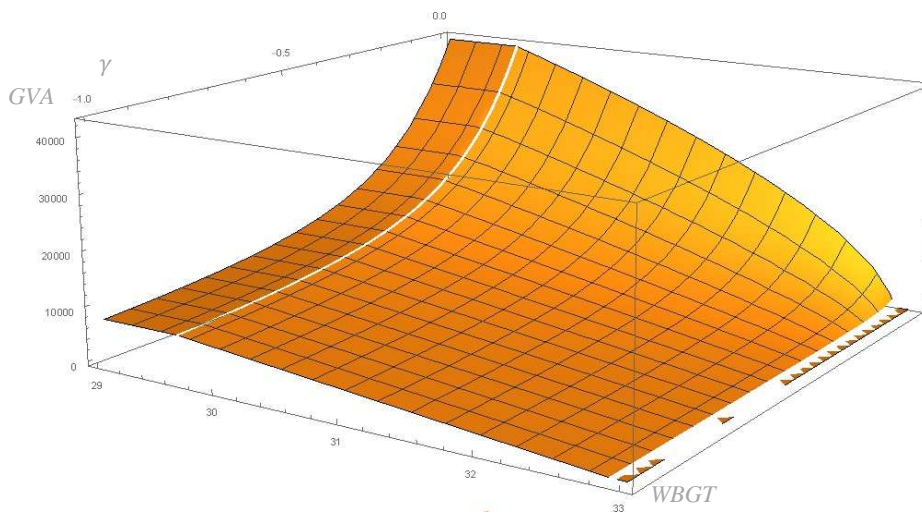
### 3.3.2 Comparative statics

Production is monotonically non-increasing in WBGT. However, for constant labour and capital levels (that is, assuming capital and labour are at their optimal level), the shape of the relationship changes depending on the capital/labour shares ( $\theta$ ) and the elasticity of substitution (measured by  $\gamma$ ).

Figure 3-10 and Figure 3-11 depict GVA for a sector of intensity  $WI_2=240W$  as a function of WBGT and elasticity, assuming the same temperature is observed for all working hours within each day. GVA is depicted on the y-axis, WBGT on the x-axis and  $\gamma$  on the z-axis. The production function is calibrated to mimic the manufacturing sector in Antwerp. Figure 3-10 uses capital/labour share  $\theta = 0.4$  and Figure 3-11  $\theta = 0.7$ . For low values of  $\gamma$  (high elasticity), a decrease in capital shares reduces the concavity of the function, thereby causing higher decreases in GVA as temperature increases.

Intuitively, this means that the higher the share of labour input in a given sector, the larger the costs of heat through productivity losses. For a given capital/labour share, decreasing the elasticity of substitution (i.e., increasing  $\gamma$ ) has the same effect. This is intuitive and means that if it is difficult to substitute labour with capital in production, as labour become less productive, losses increase faster. This is clear in both figures when comparing the inclinations of the functions at  $\gamma = -1$  and  $\gamma = 0$ . Finally, for high values of  $\gamma$  (low elasticity), increasing the share of capital decreases the responsiveness of GVA to a marginal increase in WBGT for low levels of the latter, but increases it for high levels of WBGT.

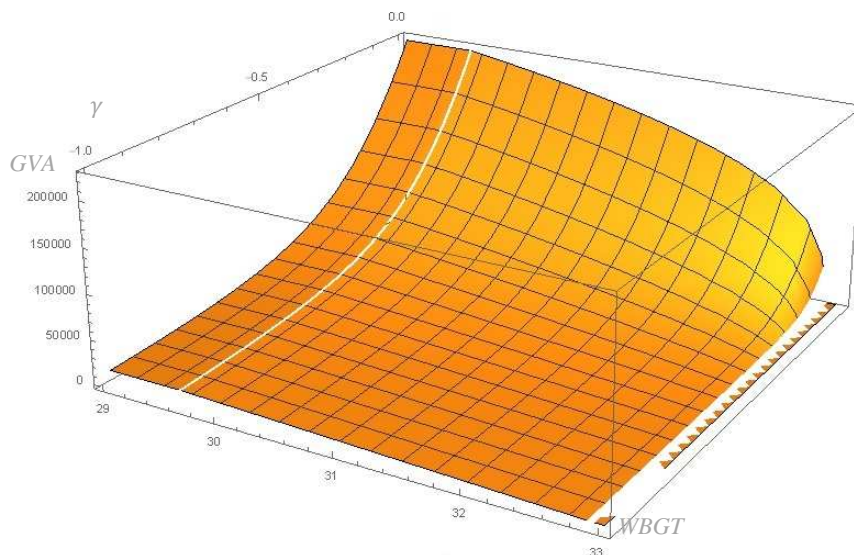
Figure 3-10 GVA as a function of WBGT and elasticity;  $\theta=0.4$



Notes: GVA for a sector of  $WI_2=240W$  as a function of interior WBGT and  $\gamma$ ;  $\theta=0.4$ .

The values for A, L, and K are set to mimic the manufacturing sector in Antwerp.

Figure 3-11 GVA as a function of temperature and elasticity;  $\theta=0.7$



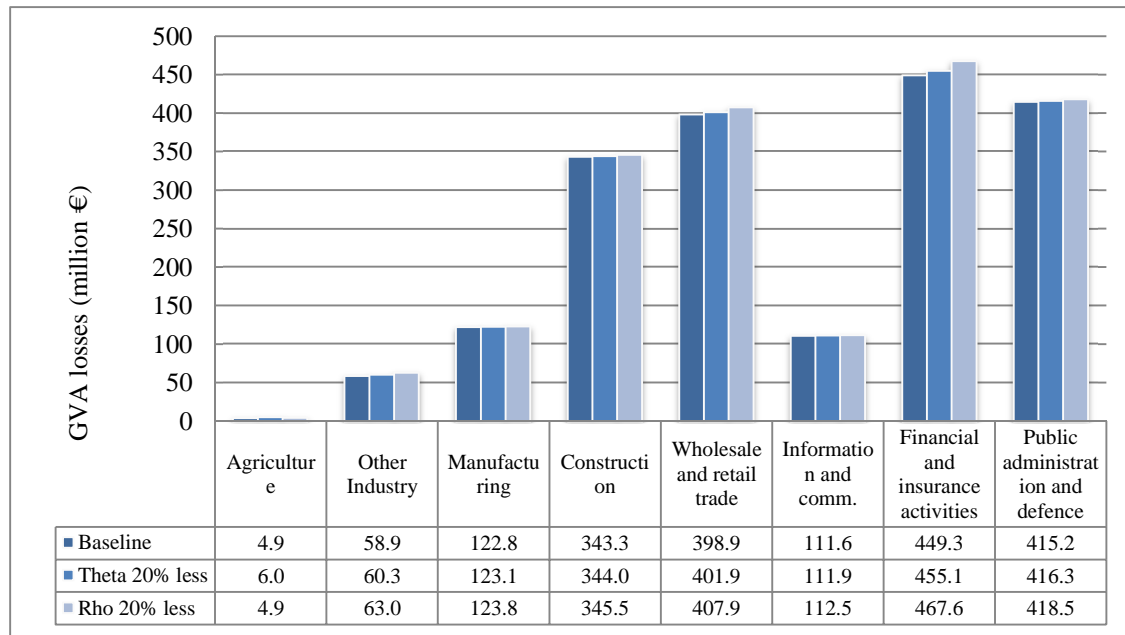
Notes: GVA for a sector of  $WI_2=240W$  as a function of interior WBGT and  $\gamma$ ;  $\theta=0.7$ .

The values for A, L, and K are set to mimic the manufacturing sector in Antwerp.

Finally, we study how losses to GVA across sectors vary when we change the parameters of the production function. Figure 3-12 depicts losses to GVA for each of the sectors of the London economy. The baseline uses the actual London calibration of the function, in a warm year in the far future. We compare this with the baseline calibration but with first a  $\theta_s$  20% smaller, and second a  $\rho_s$  20% smaller (where  $\rho_s = \frac{1}{(1-\gamma_s)}$ ), for each sector  $s$ .



Figure 3-12 Losses to GVA for different parameters; London



Notes: Losses to GVA for the baseline scenario, for  $\theta$  of less 20% in each sector, and  $\rho$  of less 20% in each sector. Results for the London economy in a warm year in the far future.

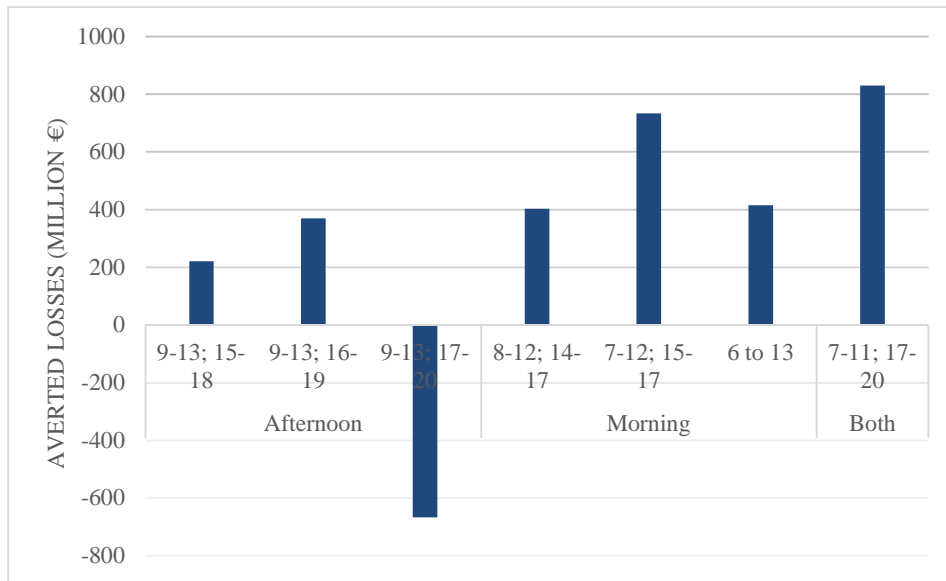
In all sectors decreasing capital shares increases losses, and in all but agriculture a decrease in elasticity has an even larger impact in increasing losses.

In terms of which sectors’ losses make up a higher share of losses, the weight of the manufacturing, construction, and public administration and defence sectors in the total amount of losses decreases for both scenarios, while all the others increase. These are the sectors with the lowest elasticities of substitution, which makes them more responsive to both changes in capital shares and elasticity itself, as can be inferred from Figure 3-10 and Figure 3-11.

### 3.3.3 Impact of adaptation measures on averted losses

We first focus on behavioural adaptation by estimating the impact of changing working hours in terms of averted losses for labour productivity. In all three cities, the morning working schedules seem to lead to better results than the afternoon schedules, with the schedule that performs the best being 7h-11h; 17h-20h. Figure 3-13 depicts losses in London in a warm year in the near future (the year with the largest losses in the city) under different working schedules.

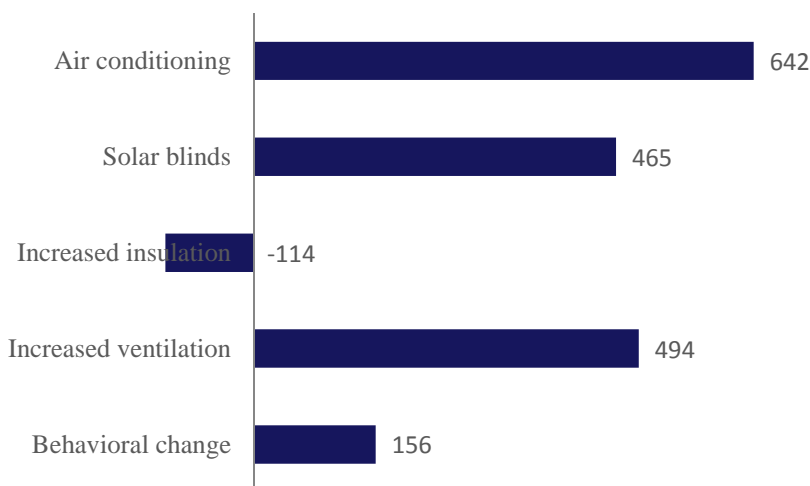
Figure 3-13 Averted losses under different working hours



Note: Results for London, for a warm year in the near future

Finally, we compare across all adaptation measures. Unsurprisingly, air conditioning is the most effective in reducing labour productivity losses from heat stress. Increased ventilation performs well and solar blinds are almost as effective in reducing losses. Increased insulation, on the other hand, increases losses. This is because, in the absence of increased ventilation, more heat is trapped inside the building. Figure 3-14 presents averted losses from alternative adaptation measures for Antwerp, for a warm year in the far future. The behavioural change presented is the working schedule 7h-11h; 17h-20h, the most effective for the case of Antwerp.

Figure 3-14 Averted losses under alternative adaptation



Note: Antwerp, warm year in the far future. Values in million €

### 3.3.4 Adaptation and energy demand

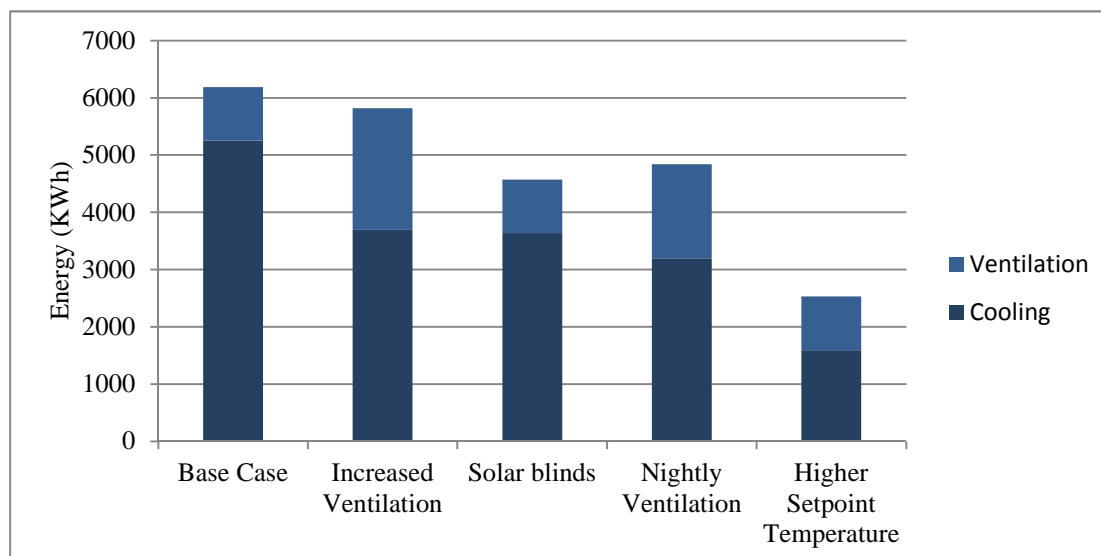
We first focus on the energy cost in a ventilated building during the reference period in Antwerp, and compare the results for the different hard adaptation measures. For simplicity, we assume that the workers use the baseline working hours. When comparing the cooling costs for the adaptation scenarios in which the mechanical ventilation is increased, we should also take into account the increased ventilation costs. Hence, Figure 3-15 shows the average yearly cooling and ventilation demand during summer in the course of the reference period.

The ventilation cost only depends on the ventilation system, and hence it is the same for the base case, the building with solar blinds and the building with an increased higher setpoint temperature, augmenting to 937 kWh for the entire floor for one summer. For the building in which the ventilation rate is increased and the building with increased nightly ventilation, the costs of the ventilation are higher, being respectively 2130 kWh (more than twice the cost for the base case) and 1650 kWh.

Summing the ventilation and the cooling demand for the base case building (with base line working hours), a total energy demand of more than 6200 kWh per summer for the reference period is observed. All the adaptations measures that are considered in the study reduce the total energy costs, but the effect varies greatly between the different options. Increasing the ventilation effectively reduces the cooling demands, but due to the increased ventilation demands, the net effect is only minor (reduction by 7% to 5800 kWh).

Adding solar blinds or increasing the nightly ventilation have approximately 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, keeping into account the smaller ventilation costs for this option, yields a slightly higher total energy demand reduction of 28%. The largest effect is obtained by increasing the thermostat setpoint from 25°C to 31°C. In this way, the tolerated temperature in the office building increases dramatically, but the cooling costs are more than halved, being reduced to 2500 kWh.

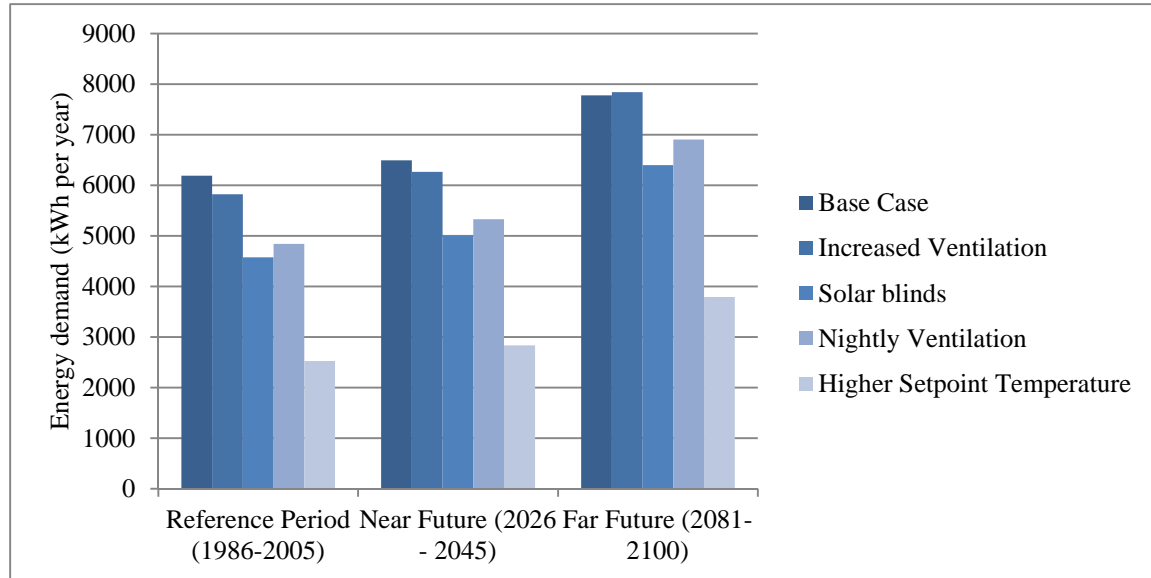
Figure 3-15 Energy demand for Antwerp: Reference period



Note: average yearly cooling and ventilation demand during summer (May-September) in the course of the reference period assuming baseline working hours.

Figure 3-16 shows the future cooling costs in Antwerp, using the RCP8.5 scenario and the GFDL-ESM2M model to estimate the future urban climate for the near future (2026-2045) and the far future (2081-2100). We again show average results for twenty years periods, and only focus on results for the summer period (May – September).

Figure 3-16 Energy demand in Antwerp: time evolution



Note: Results for baseline working hours and the combination of the cooling and the ventilation demand, averages for summer period (May-September).

As expected, the cooling costs increase dramatically between the current period and the near and the far future. 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. In a period of 100 years, the energy demand for the base case building increases by 25% from 6200 kWh to 7800 kWh. The increases for the adapted buildings are more or less similar, but are slightly dependent on the details of the adaptation measures. For the far future runs, anew, the smallest cooling costs (3800kWh) are observed if the setpoint temperature is increased to 31 °C.

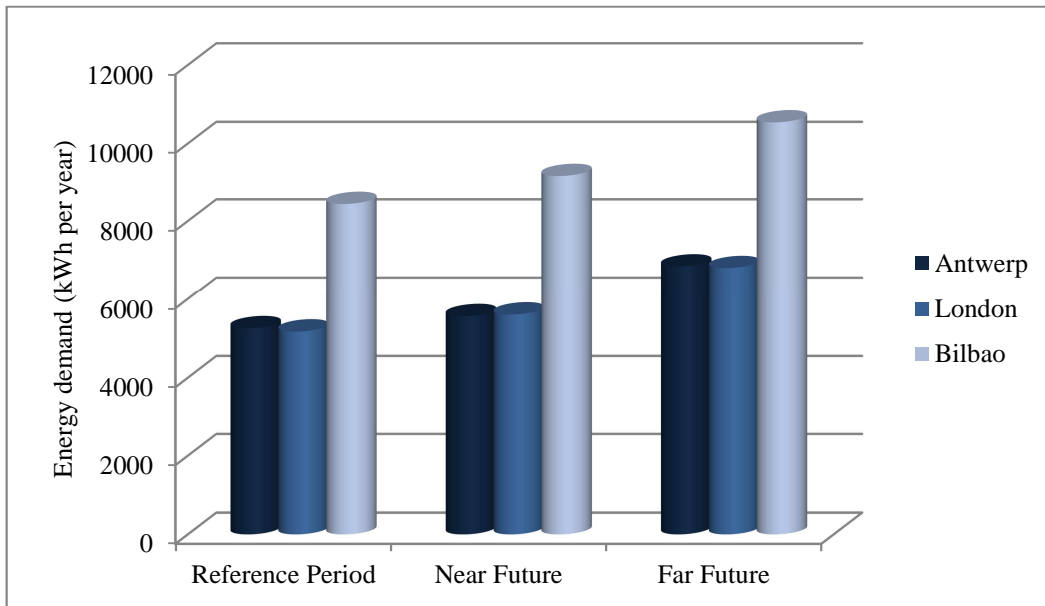
Figure 3-17 shows the cooling demands for Bilbao, London and Antwerp, using the unadapted building. Cooling demands are, as expected, much higher in Bilbao, while more or less similar results are observed for London and Antwerp.

The difference between the cooling costs in Antwerp and London in the reference period is below the uncertainty margin of this study, but there is a significant higher cooling demand<sup>8</sup> in the lower-latitude city Bilbao, where the average demand is 1.6

<sup>8</sup> Note that the ventilation demand is the same in the three cities (since the same ventilation system is applied in all three cities), hence we only focus on the (temperature-dependent) cooling demand.

times as large as the one in Antwerp and London. Similar results are observed for the future time frames.

Figure 3-17 Cooling demand for the reference period and future periods



Note: Demand in kWh per year for the reference period and future periods 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.

### 3.3.5 Benefit/cost ratios of air conditioning

In order to examine the use of our cost methodology for estimating benefit/cost ratios of adaptation measures, we explored the costs and benefits of air conditioning based on energy demand. As with the other estimates in this report, the purpose was purely to illustrate the use of the methodology, not to provide comprehensive benefit/cost ratios. For example, we account only for energy costs of operating the air conditioning, without including installation or maintenance costs of air conditioning units. Similarly, we do not project energy prices into the future.

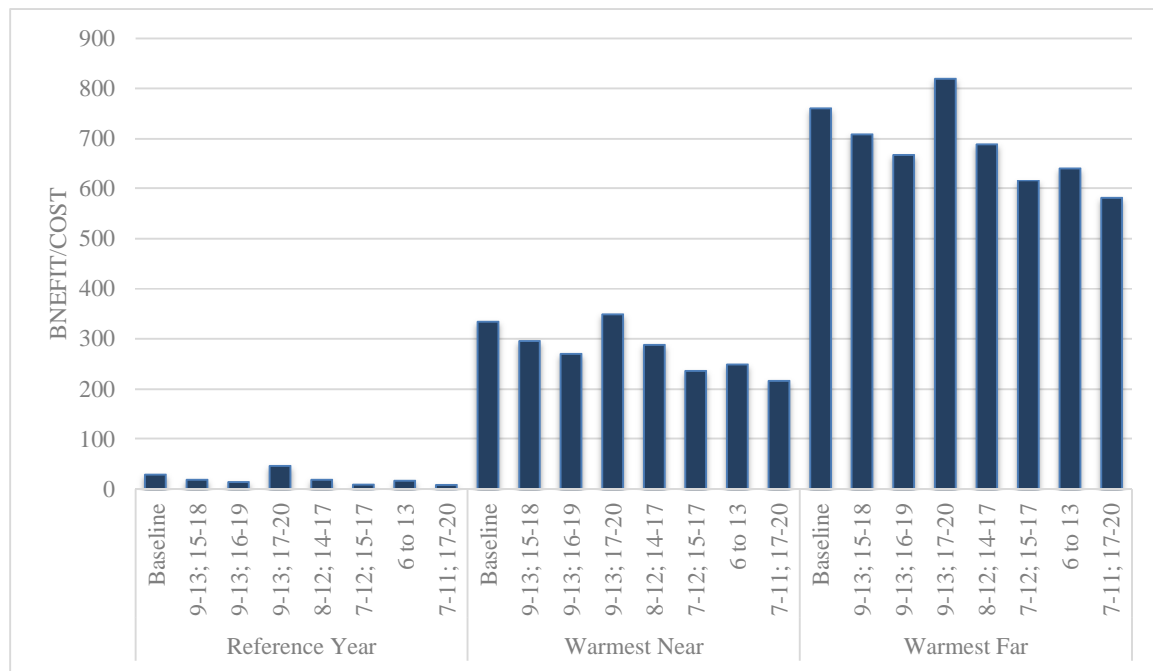
We chose a setpoint of 31 degrees C, which is the threshold below which indoor productivity losses are assumed to be zero under ISO standards. Given that the energy demand was estimated for a five month period (May-September) and the economic losses were estimated conservatively assuming heat impacts in only two months of the summer (taking account of summer holiday periods), we assume the energy demand is constant across the five month period and estimate the costs for only two of these months.

We calculate benefit/cost ratios for the five years, for baseline working hours and the other seven working hour regimes. The ratio is always positive, and as expected becomes very high in warm years in the future. Figure 3-18 presents the benefit/cost ratio for all working regimes for Antwerp.

As well as installation and maintenance costs, which may be substantial, air conditioning may have a range of other costs that would need to be included in any comprehensive cost-benefit assessment. For example, unless the electricity supply is

decarbonised, the increase in energy demand will lead to increased carbon emissions, creating a trade-off between climate adaptation and climate mitigation. When used on a large scale, air conditioning can increase outdoor urban temperature, further exacerbating the impact of heat stress and potentially further increasing the costs of air conditioning. Finally, it may be less viable for many cities in developing countries, where access to electricity infrastructure is constrained. Consequently, city policy makers would need to consider these and other assumptions when using the methodology.

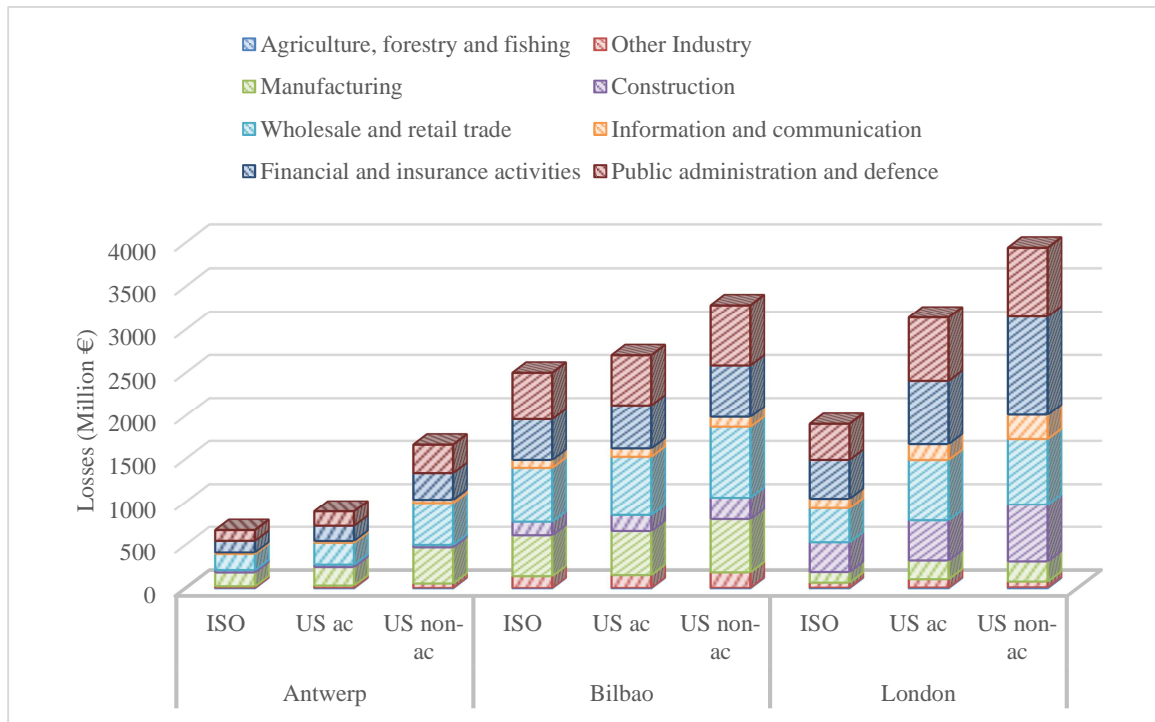
Figure 3-18 Benefit/cost ratio of air conditioning, Antwerp



### 3.3.6 Robustness: alternative productivity loss functions

As put forward in Section 3.2.1, the choice to base our productivity losses solely on ISO standards could be argued with. Accordingly, we use the alternative standards to account for productivity losses described in Section 3.2.1. The losses are always larger when using the alternative standards, implying the ISO results can be considered conservative estimates. Figure 3-19 presents the losses for the three cities and for the three standards, in a warm year in the far future, across all sectors of the economy.

Figure 3-19 Losses with different heat stress standards



### 3.4 Discussion

One of the purposes of RAMSES is to find a simplified approach to what is a complex subject, so as to achieve better science based insights. The methodology in this section presents a step towards achieving this goal. However, as with any simplified analysis of a complex subject, the consequences of which are widespread and challenging to quantify, our economic cost methodology has a number of caveats that should be taken into account when interpreting any results.

First, our model assumes heat impact is independent across time. This means that one day of heat stress would have the same effect in isolation as it would after a series of similar days. This is due to our choice of the use of legal standards to proxy for productivity losses. The actual productivity loss due to heat stress could be underestimated. In reality, productivity losses are observed at much lower temperatures due to the maladaptation of the workers to heat stress.

Although the methodology currently only focusses on the loss of working hours due to legal actions, the cost methodology is also suited to study the effects of productivity loss due to physiological maladaptation to heat stress, if the productivity loss functions based on ISO-standards are replaced by similar functions based on complete physiological surveys or comprehensive measurements of productivities in real office building. These fields are only at their infancy, but initial usable results are emerging (Seppänen, 2004).

We further assume for simplicity that productivity losses are independent across individuals, while in reality several types of labour are complementary, at the same time

the outputs of certain industries are used as inputs in others. There have also been critics to the use of WBGT as a heat stress index for individual work situations, and other alternatives have been proposed (Malchaire, 2000).

In the current framework we focus on direct, short term impacts, and do not allow for general equilibrium effects across the economy, nor for factor optimization. In the long run, when the levels of both labour and capital can be re-optimized, the economy might respond to permanent increases of mean temperatures by adjusting the factors of production. What the final effect of both heat stress and optimization would be in terms of production levels and distributional effects of income is difficult to predict.

In terms of calibration, the study presents a few limitations. First, the CES production function parameters were retrieved from different studies, based on different years and sectors. We do not account for economic or population growth. Given current trends for urban development, our results are likely to be underestimated. Since we assume losses occur only in two months in a year, we have a conservative estimation, as high temperatures are likely to take place in several months throughout the year.

In terms of temperature forecasts, two main caveats need to be taken into account. The first is that only one prototype building has been used in this report for estimating the costs, and many assumptions have been made in the design this model building. Thermal properties of buildings vary greatly based on the year in which they were built and the type of building use (e.g. warehouse, factory, office). Further research should examine heat transfers for different building classes.

The second caveat concerns climate scenarios. Although the IPCC identifies four Representative Concentration Pathways, we have, due to computational reasons, only used the strongest scenario (RCP8.5). We have moreover only used climate output of a single global climate model (GFDL-ESM2M). This model has been selected since it yields the median temperature increase in the ensemble of the 11 GCMs that has been studied in Lauwaet *et al.* (2013). Ideally, the study should be extended to take into account the entire ensemble of GCMs and other scenarios.

In terms of assessing the gross benefits of implementing adaptation measures, we compared averted losses for five different adaptation measures: behaviour change, air conditioning, mechanical ventilation, insulation and solar blinds. While this is a wider range of adaptation measures than examined in most other studies of averted losses, it inevitably does not cover the full range of potential adaptation measures available in cities. Examples of other heat adaptation measures include the reduction of internal heat gains (de Wilde, 2010; Collins, 2010), technical improvements in the performance of cooling and ventilation devices (Sclafani, 2010), and relocation of buildings. Future research should explore more of these adaptation options.

One of the objectives of the study was to develop a methodology that could be used to assess not only the benefits of adaptation (measured as averted losses), but also costs of adaptation measures. In this report, we examine the energy demand of air conditioning as an example of analysing benefits and costs of adaptation measures. The results of the energy demand analysis show that the economic cost methodology is a relatively simple method for examining benefits and costs.



While it would have been interesting to factor in and compare the costs of other adaptation measures, disaggregated data of sufficient quality were not available. This is partly because data of sufficient quality were not found in the academic literature and partly due to the substantial delay in adaptation cost data as part of RAMSES deliverable D1.3 following the departure of one of the partners from the consortium. The aim is to generate new data on commercial installation costs of adaptation measures as part of D1.3 which is now scheduled for completion in 2016. Data will be generated on the installation costs of heat adaptation measures such as air conditioning, mechanical ventilation, solar blinds and insulation, as well as flooding adaptation measures such as green roofs and permeable paving.

Our results have further focused on the three focal case study cities of the RAMSES project. Although there is a climatic difference between London and Antwerp on the one hand, and Bilbao on the other hand, all three cities have a predominantly oceanic climate (Cfb) according to the Köppen classification. Future work on cities in different climatic zones is likely to give rise to interesting results.

The results have implications in terms of inequality, both between and within cities. As it stands, heat stress is more likely to affect cities in already poorer countries, with the resulting production losses affecting these mostly these cities as well. This is likely to increase inequality between cities in different countries. Moreover, the results have implications in terms of within city inequality. Poorer individuals tend to provide non-skilled labour, often in sectors that are more sensitive to temperature stress (for example, non-skilled labour in construction or manufacturing). Assuming the labour market operates with only minor frictions, then wages are set based on worker productivity. This implies heat stress could in the long term decrease labour income, in particular where it already tends to be lower.

Finally, because we focus on the effect of heat on productivity we exclude possible benefits of increasing temperatures in certain sectors or countries. For example, agricultural productivity might increase with temperature in cold countries, where also industries such as tourism could benefit from higher temperature. We also focus on only one channel. There might also be co-benefits of adaptation to other areas of the economy that we do not account for in the present analysis. Particularly, in Section 4.2 we discuss direct health costs from heat stress. Reducing workplace heat stress would have positive benefits for general health.

## **4 Other economic costs of heat in cities**

Heat affects the urban economy through a variety of channels. In addition to labour productivity, heat stress has negative effects on health, increasing mortality and morbidity, and on urban infrastructures, namely on buildings and transport infrastructure. Based on the methodology developed here, and on research in WP3 and WP6, we focus on costs of heat through transport disruption and health.

## 4.1 Heat and transport disruption

### 4.1.1 Methods

With temperatures over 39 degrees, rails can buckle and deform, with consequences in terms of damage repairs and delays to users (Acero *et al.*, 2014). Using results from Jenkins *et al.* (2012), along with the cost methodology described in Section 2.1.3, we estimate how different heat scenarios impact London's urban economy through *delays* in the transport system, specifically, in the rail, tube and DLR.

We define labour in terms of total quantity supplied per sector, where transport disruptions imply a decrease in time spent working. Accordingly, heat stress affects the amount of labour ( $L$ ) in each of the sectors in equation (1):

$$Y_{c,s,t} = f(L_{c,s,t}, K_{c,s,t}) = A_{s,c} [\theta_s (a_{K,s} K_{c,s,t})^{\gamma_s} + (1 - \theta_s) (a_{L,s} L_{c,s,t})^{\gamma_s}]^{\frac{1}{\gamma_s}}$$

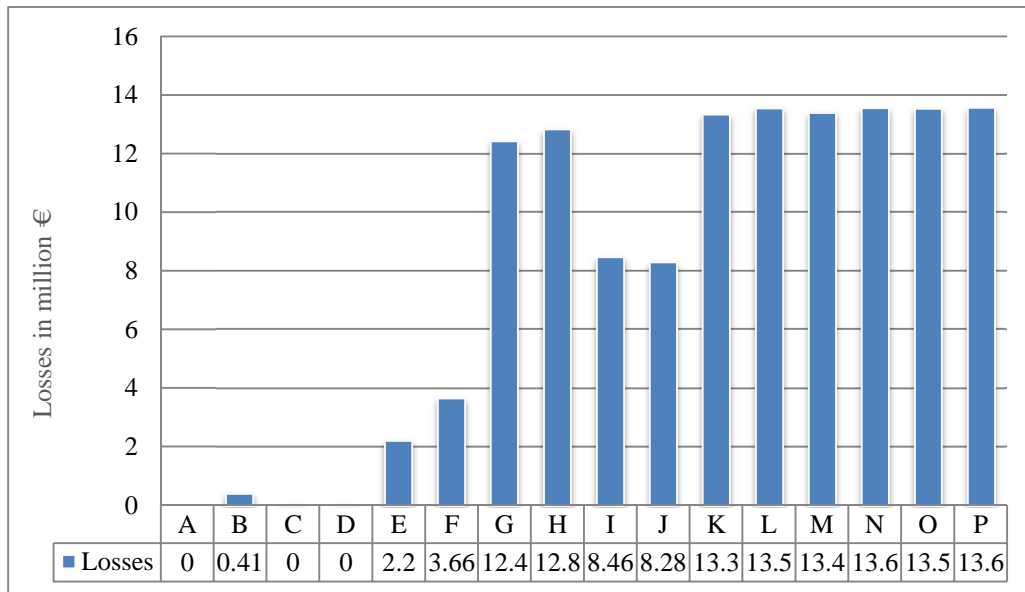
We define levels of labour in terms of person minutes and the delays are fed into the production function. For consistency with the analysis in section 2 we use the model of economic costs calibrated for the year 2005. We collect average annual working hours for the United Kingdom from the OECD statistics (1,630 hours), which we use to calculate the total minutes worked per person in a year. We assume equal work on each day of the week for simplicity. This gives us an average of 4.6 hours per person per day. We then use the calibration of  $L$  from Section 2.2.1 to estimate the number of person minutes worked per year in each sector in London.

Jenkins *et al.* (2012) use the UKCP09 High Emissions scenario to perform 100 x 30 year runs for daily data for the 2040-2069 time period. These are binned into magnitude order – from least severe to most severe heat events – and one heat event is selected at random from each bin. This gives rise to 16 scenarios, ranked by order of magnitude as measured by the number of grid cells in the Greater London area which exceed the temperature threshold for a speed restriction to be applied (scenarios A-P, from least to most severe). Using information from the current transport configuration of rail, Tube, and DLR networks and the 2001 Census about the number of journeys they then calculate the equivalent person-minute delay.

### 4.1.2 Results

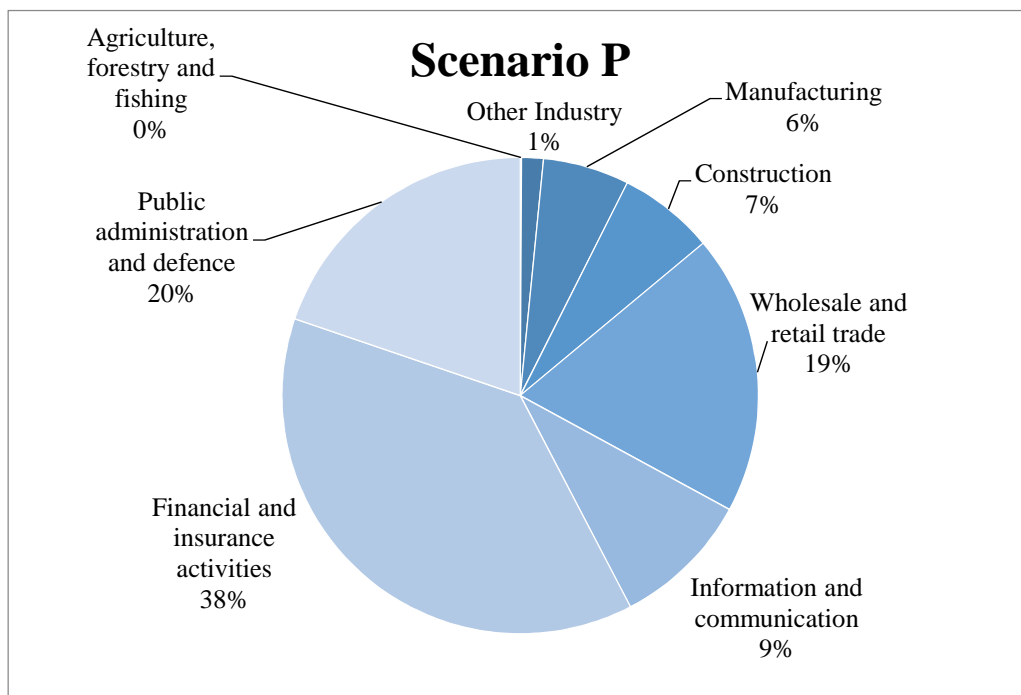
We evaluate the impact of one day of transport disruption on yearly GVA. The total person-minute delays are fed into the CES production function for an entire year. The total losses are presented in Figure 4-1 and vary between zero and €13.6 million. These are distributed between sectors as shown in Figure 4-2, which presents the sectoral breakdown of losses for the most severe scenario.

Figure 4-1 Losses due to heat under different scenarios (A-P)



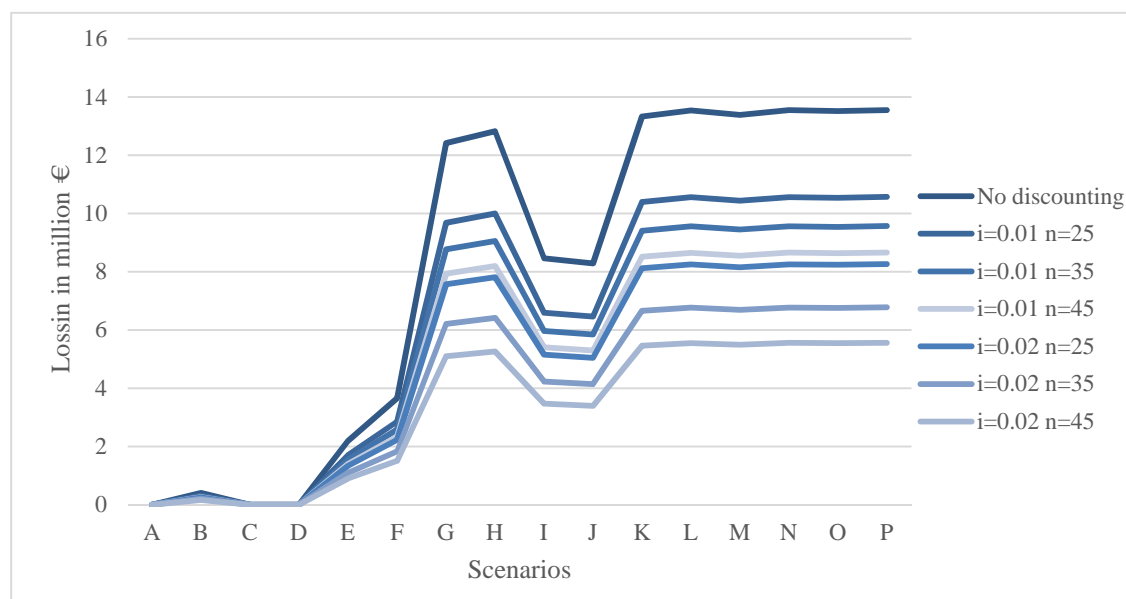
Notes: Losses in million € in absolute values. Scenarios A-P.

Figure 4-2 Distribution of losses to GVA across sectors



Finally, we calculate the net present value of losses, with a discount rate ( $i$ ) varying between zero and 0.02 and a number of years until heat event ( $n$ ) varying between 25 and 45. This is to account for the fact that the heat event can occur in any year between 2040 and 2069, roughly between 25 and 45 years from now. Resulting total costs for the most severe scenario (P) are between €5.6 million for  $i=0.02$  and  $n=45$  and €10.6 million for  $i=0.01$  and  $n=25$ . These are presented in Figure 4-3.

Figure 4-3 Net present value of losses



Notes: Losses in million € in net present values. Scenarios A-P.

### 4.1.3 Discussion

In this section we apply the methodology introduced in Section 3 to quantify losses of heat waves through a different channel: transport disruption. The transferability of the method, with a minimum requirement of additional data, is one of its most valuable aspects, and key to the objectives of RAMSES.

Here again, due to the necessary simplifications, there are a number of caveats associated with this analysis. The first and most obvious one is that this analysis accounts for the short term impact only. Production is dynamic, with a shock to a year's production being likely to have effects in the year(s) to follow. We made the strong assumption that any increased commuting time would imply an equivalent loss in working hours, implying losses occur on the way to work. Disruptions that take place on other journeys would imply costs of losses in leisure time. If the economy is at equilibrium, where wages are set to equal the marginal leisure value, the total loss to the economy in a static environment should be comparable.

Additionally, we do not explicitly account for the geographical distribution of sectors within a city. For example, some boroughs of London that are more dependent on the rail network might also concentrate highly productive activities. We also do not account for the possibility of autonomous adaptation taking place in the future. As a response to current heat events, workers may find alternative routes, which may in some cases be more efficient.<sup>9</sup> Finally, we focus only on one channel – transport disruption – and within this only on delays to users of the tube, DLR, and rail network. The results should thus be used with caution. They are meant to illustrate the use of the cost

<sup>9</sup> See Larcom *et al.* (2015).

methodology in the context of transport disruption, rather than provide exact estimates of losses.

In the context of an urban economy, these results might have additional implications in terms of losses of agglomeration economies and consequently economies of scale. Assuming an urban economy is in equilibrium, the interaction between agglomeration economies, in the form of reduced transport costs, and economies of scale of production within a city means that production will take place at a centralized level if the costs of transport are lower than the economies of scale gains from production at larger scales (Bruekner, 2011). When transport costs increase they might become high relative to the strength of scale economies, and production may become dispersed, with the associated loss of economies of scale.

## 4.2 Heat and direct health costs

Within Work Package 6, a case study on health impacts of heat under climate change was conducted in the metropolitan area of Skopje (FYROM), Macedonia. After ascertaining the relationship between ambient air and mortality at baseline (years 1986-2005), the evolution of the city population and of ambient temperatures was modelled under a Representative Concentration Pathway scenario (RCP8.5) in two future time windows: 2026-2045 and 2081-2100. The projected average annual mortality attributable to heat was then calculated during those time windows.

### 4.2.1 Methods

In the absence of local studies in Macedonia, WP6 used as a reference the EU-wide values from the background studies for the revision of the EU air policy (Holland *et al.*, 2005 and Holland, 2014), extrapolated the value of a statistical life (VSL) through “benefits transfer” (OECD, 2010):

$$VSLp' = VSL_s \left( \frac{Y_p}{Y_s} \right)^\beta \quad (5)$$

Where VSL<sub>s</sub> is the original VSL estimate from the study, Y<sub>s</sub> and Y<sub>p</sub> are the income levels in the study and policy context, respectively, and β is the income elasticity of VSL (in terms of willingness to pay for reducing the mortality risk). As for the value of β, 1.0 was assumed for the general public as suggested by Viscusi (2010). The resulting VSL used for calculation was €571,604 (Low: €376,46; High: €766,744). Regarding the averted mortality costs through adaptation, it is unclear exactly how effective heat-health action plans are in preventing heat-related mortality and morbidity. A recent review on the matter (Toloo *et al.*, 2013a and Toloo *et al.*, 2013b) confirmed this point. However, a relatively recent French study (Fouillet *et al.*, 2008) suggested an effectiveness of about 68% in excess mortality prevention.

## 4.2.2 Results

The resulting numbers of attributable deaths are presented in Table 4-1. The “Minimal” climate model is the MRI-CGCM3 model (Seiji *et al.*, 2012), the “Median” climate model is the GISS-E2-R model (Schmidt *et al.*, 2014) and the “Maximal” climate model is the IPSL-CM5A-MR model (Dufresne *et al.*, 2013) climate models.

*Table 4-1 Mean, 10th percentile and 90th percentile of the distribution of attributable deaths per year in Skopje*

	1986-2005	2026-2045			2081-2100		
	Climate model*	Climate model			Climate model		
Population model	Median	Median	Minimal	Maximal	Median	Minimal	Maximal
Exponential	58 (36; 85)	124 (84; 170)	100 (63; 143)	125 (80; 185)	272 (163;388)	223 (148; 301)	366 (232; 512)
Logistic K= 700,000	55 (34; 81)	117 (80;161)	95 (60; 135)	118 (75; 174)	226 (137; 321)	186 (123; 250)	304 (194; 422)

Notes: For the reference time lap 1986-2005, the three climate models overlap and correspond to the observed scenario.

Table 4-2 presents the average annual projected mortality costs in Skopje (FYROM) in million € of 2005 without adaptation during the timeframes of 2026-2045 and 2081-2100 and the avertible heat-related mortality costs through health adaptation.

*Table 4-2 Costs of mortality and averted losses through adaptation*

Period	Avg. annual cost heat-related mortality	Avertible cost through adaptation
2026-2045	70.87 (48.01 – 97.17)	48.19 (32.65 – 66.07)
2081-2100	154.90 (93.17 – 221.78)	105.33 (63.36 – 150.81)

Note: Median VSL value was used; CI comes from epidemiological evaluation, with population projected through an exponential model. Costs in million €.

## 4.2.3 Discussion

The analysis on the economic costs of heat waves summarized in this section and developed in WP6 is complementary to that of Section 3. Heat waves and high temperatures impact the health of individuals that seek medical treatment, but also to a lesser extent that of those that still perform their professional activities. A comprehensive estimate of the health costs of heatwaves through the city economy would require both cost methodologies to be integrated. The way in which the different methodologies were develop implies that future research could easily integrate the direct health impacts of heat stress with productivity losses for a broader understanding of health impacts of heat waves on the urban economy.

This analysis presents several limitations. On the physical impact side, the analysis: 1) Did not consider possible variations of the heat-mortality curve over time due to

population acclimatization/mitigation/adaptation; 2) Did not stratify by age due to the difficulty in obtaining stable estimates of the heat-mortality relationship for population subgroups; 3) Assumed independence of future population size and climate conditions; and 4) Used only one Representative Concentration Pathway climate scenario. On the economic modelling side, it did not include cost of illness from morbidity health outcomes. That analysis is planned for the case study city.

## 5 Economic costs of flooding in cities

### 5.1 Pluvial flooding and transport disruption costs

The methodology described in Section 3.1 can be used to estimate damage costs related to other climate hazards. In Deliverable 5.1 we identify vulnerable aspects of the transportation network in relation to climate change. In addition to high temperatures, the main climate hazards having a negative impact on urban transport are storms and flooding. Based on work from WP3, we focus on the latter. As with the case of transport disruptions due to heat waves (Section 4.1), floods that affect the transport system are assumed to have a negative impact on the amount of labour supplied.

#### 5.1.1 Methods

Flooding events are major threats affecting cities. They may take the form of coastal flooding or they may take place inland, as a result of rainfall (pluvial flooding) or due to river overflows (fluvial). Due to the large amount of sealed surface areas in the urban landscape, more frequent and severe precipitation causes a larger incidence of flash floods in cities (Floater *et al.* 2014). One of the main consequences of flooding events is a disruption to transport networks due to flooded rail tracks, roads and underground systems.

The same methodology described in Section 4.1.1 can be used to assess the damage to the London economy resulting from a flooding event. We again define labour in terms of total quantity supplied per sector, where transport disruptions imply a decrease in time spent working. Thus floods affect the amount of labour ( $L$ ) in each of the sectors in equation (1):

$$Y_{c,s,t} = f(L_{c,s,t}, K_{c,s,t}) = A_{s,c} [\theta_s (a_{K,s} K_{c,s,t})^{\gamma_s} + (1 - \theta_s) (a_{L,s} L_{c,s,t})^{\gamma_s}]^{\frac{1}{\gamma_s}}$$

Analogous to Section 4.1., we define levels of labour in terms of person minutes and the delays are fed into the production function. We use the production function calibrated for the year 2005 and calibrate annual working hours as described in Section 4.1. We use predicted delays estimated in WP3. WP3 uses CityCAT, along with the London road network, to predict delays resulting from a one hour 100 year flooding event. It uses two scenarios: one where the city is completely permeable and one where it is impermeable. The person-minute delays are calculated using the 2011 Census data on daily journeys.

### 5.1.2 Results

The total person-minute delays from a one hour event, in one day of the year, are fed into the CES production function for an entire year. The resulting total losses are estimated at €2.73 million even in the completely permeable scenario, and €979 million as a result of a one hour flooding event in one of the days in the completely impermeable scenario.

### 5.1.3 Discussion

The application in this section is useful to portray the transferability of the cost methodology introduced to different climate hazards. By defining the hazard in terms of its effect in different inputs of the production function across sectors, various hazards can be studied using a comparable method.

In terms of the costs estimated, the same limitations out in Section 4.1.3 apply here, with particular emphasis on the geographical distribution of transport disruptions. Some boroughs of London that concentrate highly productive activities might be more prone to flooding, and a geographically disaggregated analysis would be necessary to evaluate the full effects of flooding on economy through transport disruptions.

## 5.2 Sea flooding and city losses

Using a different methodology, Work Package 1, namely in Deliverable 1.2, estimates damage functions for the three case studies for different levels of sea rise. It focuses on direct damages to assets, based on estimated flood depths and different classes of land cover and land use. Additionally, the costs of sea defences are estimated for varying heights. The work is described in Deliverable 1.2 and Boettle *et al.* (2016).

### 5.2.1 Methods

The damage estimation is based on a GEV approach following the formula for the expected annual damage (EAD):

$$EAD = \int_{\text{Prot.level}}^{\infty} p(x; \xi, \sigma, \mu) D(x) dx \quad (5)$$

Where  $p(x; \xi, \sigma, \mu)$  denotes the GEV probability density function and  $D(x)$  the damage function of the considered case study. The averted annual damage is the difference between the current EAD and the EAD with a presupposed “Protection level”.

All calculations are based on current environmental conditions. Information on extreme sea levels was obtained from the Joint Research Centre (JRC). The JRC provided the sea levels for the return periods 5, 10, 20, 50, 100, 200, and 500 years. From these they estimated the parameters of the corresponding Generalised Extreme Value (GEV) distribution. The following sets of parameters have been deduced:



Antwerp/Brussels:  $\xi = -0.1308$  (shape),  $\sigma = 0.4365$  (scale),  $\mu = 5.0492$  (location)  
 London:  $\xi = -0.1386$  (shape),  $\sigma = 0.1997$  (scale),  $\mu = 5.2583$  (location)  
 Bilbao:  $\xi = -0.1754$  (shape),  $\sigma = 0.0778$  (scale),  $\mu = 3.2840$  (location)

The functions are then combined with land cover data, which is translated into different categories of land use (Huizinga, 2007).

Current protection levels are set out in Table 5-1. These values are obtained from Jorisson et al. (2001) and Wood et al. (2005).

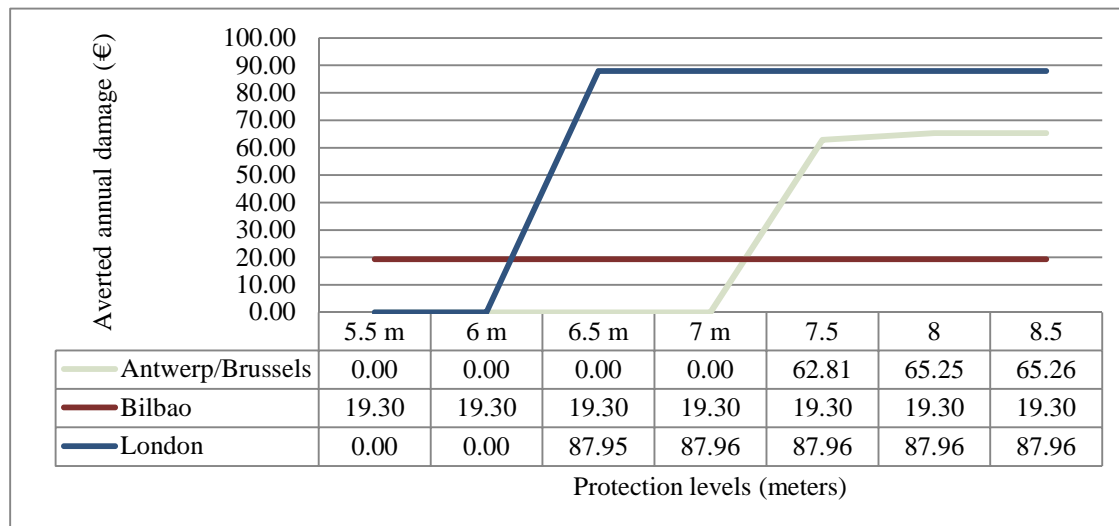
Table 5-1 Current protection levels in the three case study cities

	Antwerp/Brussels	London	Bilbao
Current protection level (return period) [yr]	1000	1000	100
Current protection level [m]	7.03	6.15	3.52

## 5.2.2 Results

Figure 5-1 presents estimated averted annual losses from sea level rise from different of increased protection heights. All calculations are based on current environmental conditions. Any increase above 8 meters does not increase averted losses because, under current environmental conditions, there is no residual damage with a protection of 8 meters in either of the three cities.

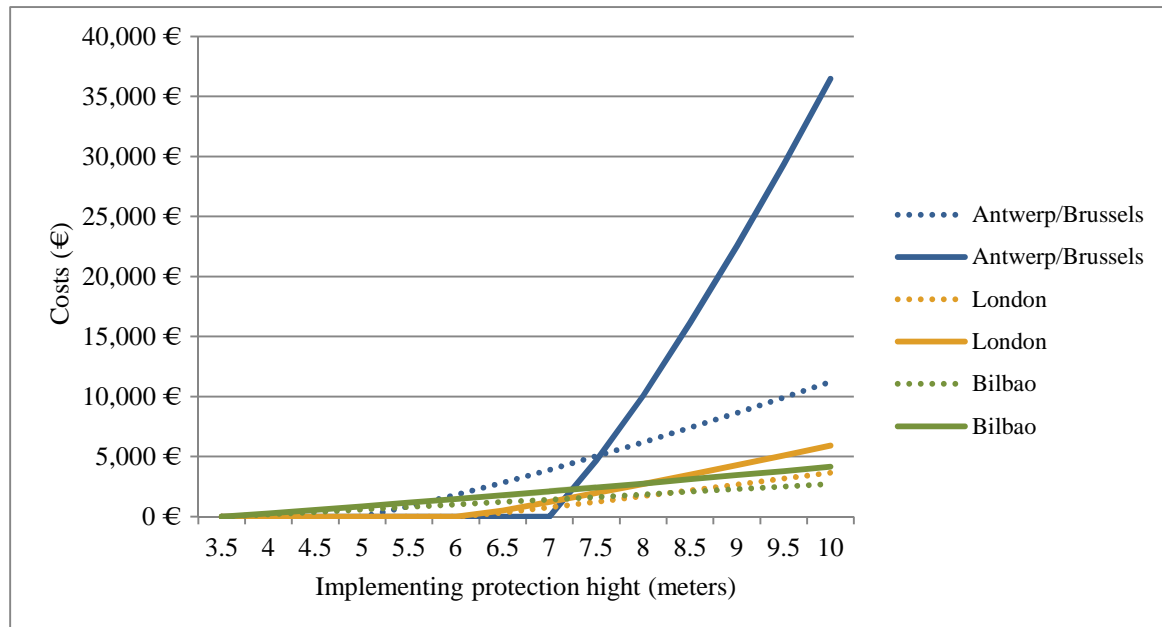
Figure 5-1 Averted damage for different protection levels



Finally, they estimate construction costs for different levels of protection. The construction costs for the reinforcement of the existing measures are based on unit costs obtained from Jonkman *et al.* (2013), where the costs per kilometre length and metre height is given to lie between €0.8 and €12.4 million (on non-urban area) and €15.5 and €22.4 million (on urban area). The values have been adjusted to 2014 values by the

country factors of 1.0977 (Belgium), 1.1398 (UK), and 0.9212 (Spain). Details on the factors can be found in RAMSES deliverable 1.2. The derivation of the required course of the protection measures can be also found in RAMSES deliverable 1.2. The high and low estimation of costs for each case study city are presented in Figure 5-2.

Figure 5-2 Costs of protection for different heights



### 5.2.3 Discussion

Unlike the analyses in the previous sections, this section focuses on direct damages to physical assets. The impact of sea level rise on productive activity can take place through several channels, such as transport disruptions, decreases in investment, or destruction of capital. The results of the present analysis could be integrated into the cost methodology of Section 2 by focusing on the destruction of productive capital.

Under the current formulation, costs of sea level rise are likely to be under-estimated, given that they are based on current environmental conditions. Further discussion of the limitations of the results are presented in Deliverable 1.2 (Part II, section 8.3).

## 6 Data for the RAMSES common platform

### 6.1 RAMSES common platform and European Clearinghouse

In order to increase transparency and provide much needed data for research and policy making, all the results of the present study have been uploaded into the RAMSES

common platform “The Climate Impacts: Global and Regional Adaptation Support Platform – RAMSES City Module” ([www.pik-potsdam.de/~wrobel/ramses/](http://www.pik-potsdam.de/~wrobel/ramses/)). The platform will later be integrated into ClimateAdapt - the European Clearinghouse (<http://climate-adapt.eea.europa.eu/>).

Through this platform the RAMSES project results are made publicly available for scientists in different fields and different levels of expertise as well as for interested laymen who want to know more about advancement in city science. The platform includes data relating to each case study city of the project, and is regularly updated to include new findings.

## 6.2 Cost and economic data

The data uploaded on economic costs includes the results of the heat and productivity study, as well as those of the same cost methodology applied to heat and transport disruptions (Section 4.1) and flooding and transport disruptions (Section 5.1). It also includes additional cost results from other RAMSES work packages, namely health costs of heat (Section 4.2) and direct costs to assets from sea level rise (Section 5.2). Table 6-1 summarizes the costs datasets included.

*Table 6-1 Cost datasets included in the Common Platform*

Datasets	Dataset 1	Dataset 2	Dataset 3	Dataset 4	Dataset 5
Threat	Heat	Heat	Heat	Pluvial flooding	Sea flooding
Channel	Productivity	Transport	Health (mortality)	Transport	Direct asset costs
City	Antwerp, Bilbao, London	London	Skopje	London	Antwerp, Bilbao, London
Time	2005; 2026-2045; 2081-2100	Present	; 2026-2045; 2081-2100	Present	Present
Adaptation	Behavioural change; increased ventilation; solar blinds; insulation; air conditioning; nightly ventilation; increased setpoint	-	Health adaptation	Full permeability	Sea protection

## 7 Conclusions and implications for future work

One of the overarching goals of the RAMSES project is to provide quantified evidence of costs of climate change in urban areas. In particular, it aims to develop transferable methodologies that can be used by researchers, policy makers, and other stakeholders, to assess these costs and compare them across cities. As part of this goal, we provide here in this report an economic cost methodology to assess the impacts of specific climate change hazards through different channels of urban productive activity. The

methodology is of an intermediate level of complexity and is transferable across cities in Europe as well as for cities in developing and developed countries internationally.

Our economic cost methodology not only provides estimates of production costs from increasing temperatures or extreme heat and flooding events, but also highlights the vulnerability of different economic sectors and the key mechanisms affecting production losses. This is important for identifying the most effective climate change adaptation strategies or economic recovery plans for specific cities, and also provides the beginnings of a framework for understanding vulnerability at the European and global levels through the lens of city economic production. The methodology is moreover relatively transferable to different urban contexts with minimal requirement of economic data.

The methodology brings together the work of several work packages (WP1, 2, 3, 4, 5 and 6) and provides a useful starting point for further work in the direction of an overall framework for assessing urban costs of climate change. The results of the economic cost methodology presented here directly feed into further RAMSES work. In particular, the methodology can be integrated into the overall cost assessment framework of Deliverable 5.4 – the ultimate goal of Work Package 5.

A novel aspect of the economic cost methodology developed in this report is its scope to analyse the factors of production at the city level. Loss functions are attributed to sectors of the metropolitan economy according to average work load of workers in each respective sector. We also define constant elasticity of substitution production functions for each sector that specifically encompass the productivity loss functions. The production functions are calibrated with economic data and aggregated at the city level according to specific weights given to each sector. This approach allows us to assess various characteristics of urban production, including the flexibility of the productive system in terms of the degree of substitutability between labour and capital, its labour intensity, and the relative importance of different sectors in the economy.

While the methodology developed in this report is one of the first transferable methods focusing on production losses across sectors of the city economy, its application will depend on the quality of data available for inputs, as well as the assumptions underpinning each step of the modelling and estimation process. Further research will be required to address a number of caveats in the methodology before it can be used as a city-level tool. However, even with the limitations of the data available for our analysis, broad conclusions on the importance of the structure of a city's economy on its vulnerability to costs and the potential for adaptation can be drawn.

One area where data are particularly scarce at the city level is in terms of adaptation costs. One of the advantages of the economic cost methodology set out in this report is its capability for estimating averted losses (gross adaptation benefits) for direct comparison with benchmarked damage costs without adaptation. We show that comparable averted losses can be estimated for a range of adaptation measures such as behaviour change, air conditioning, mechanical ventilation, insulation and solar blinds.

The methodology is also promising for integrating the costs of adaptation measures. In this report, we examine the energy demand of air conditioning as an example of analysing benefits and costs of adaptation measures. While it would have been interesting to factor in and compare the costs of other adaptation measures, disaggregated data of sufficient quality were not available. This is partly due to the substantial delay in adaptation cost data provided by RAMSES deliverable D1.3

following the departure of one of the partners from the consortium. The aim is to generate new data on commercial installation costs of adaptation measures as part of D1.3 which is now scheduled for completion in 2016. Data will be generated on the installation costs of heat adaptation measures such as air conditioning, mechanical ventilation, solar blinds and insulation, as well as flooding adaptation measures such as green roofs and permeable paving.

Looking forwards, the findings of this report will be fed into the over-arching cost assessment framework to be developed in Task 5.5 and delivered in D5.4. Furthermore, the work in WP1 and WP3 will be used to explore the transferability of the methodology to other adaptation measures (such as flooding adaptation), while the potential for integrating direct health costs of heat waves in WP6 with the indirect productivity costs discussed in this report will be discussed in D5.4.

Overall, the economic cost methodology appears to provide a strong basis for developing a transferable assessment framework at an intermediate level of complexity that can link top down and bottom up data and approaches. The RAMSES partners will therefore explore potential applications for the methodology further.

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