Impacts of climate change on indoor thermal comfort in typical Swedish residential buildings

Assessing risks for human health

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Master thesis in Energy-efficient and Environmental Building Design

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Lund University

Lund University, with eight faculties and several research centers and specialized institutes, is the largest establishment for research and higher education in Scandinavia. The main part of the University is situated in the small city of Lund which has about 112 000 inhabitants. A few departments for research and education are, however, located in Malmö. Lund University was founded in 1666 and has today a total staff of 6 000 employees and 47 000 students attending 280-degree programs and 2 300 subject courses offered by 63 departments.

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The degree project is the final part of the master program leading to a Master of Science (120 credits) in Energy-efficient and Environmental Buildings.

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Abstract

There is strong evidence that climate change has a direct impact on humans and extreme temperatures have been linked to negative health impacts and increasing mortality. The heat wave of 2018 caused up to 8.2% more deaths compared to the year before in Sweden, with higher impacts in other parts of the world. The fact that people spent almost 90% of their times indoors makes the indoor environment susceptible to increase the effect of human temperature exposure. This master thesis assessed the effects of climate change on the indoor thermal comfort and further analyzed the impacts on human health due to temperature exposure. Projections of typical and extreme future climate conditions until the end of the 21st century were used to simulate the indoor temperatures and heating demand of three different constructions of the same building type; original building, retrofit and new design. The indoor temperatures and heating demand were simulated with IDA ICE using future climate projections for three different locations in Sweden; Malmö, Stockholm and Umeå. The health impact assessment was projected with the use of temperature-related morbidity and mortality calculations, with the variation of two different human age groups. Results showed, that the implementation of energy efficient measures for the retrofit and new designed building reduce the heating demand with up to 62%. Simulations of the three constructions indicated highest number of overheating hours (hours over 26°C) in the original building and thermal comfort assessment showed that elderly (65+) experience on average 10% higher discomfort compared to young adults, if a 24h occupancy is considered. In contrast to the findings of the thermal comfort assessment, projection of the future morbidity and mortality indicated the highest risk for people living in the new designed building, where indoor temperature reach up to 34.4°C, with highest effects on elderly people. Future climate projections indicated that Malmö has the highest susceptibility for increased human health impacts compared to Stockholm and Umeå.

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1 Introduction

There exist strong evidence confirming that climate change has been affected and accelerated by human activities due to the emission of greenhouse gases (GHG) (IPCC, 2021). According to the International Panel for Climate Change (IPCC) the earth's temperature has increased 1.1°C since 1850-1900 and is expected to increase with 1.5 – 2°C within the next years due to human activity (IPCC, 2021). Extreme hot events are expected to increase in frequency, resulting in higher global average temperature. Impacts of climate change on human health and comfort are considerable, inducing risks with multifaceted consequences (WHO, 2018a).

Northern European countries are expected to experience a higher increase in temperature and precipitation compared to southern countries (IPCC, 2014). The *Swedish Commission on Climate and Vulnerability* is expecting that Sweden's climate will experience more warming than the global average, with increasing number of warm summer days and nights and decreasing number of cold winter nights and frosty days. An increase in average temperature of 2°C is expected by the 2020's, 2-3°C by the 2050's and 3-5°C by the 2080's (Swedish Commission, 2007). The year 2021 counts as the seventh warmest year ever recorded, with an average temperature increase of 1.11°C above the pre-industrial era levels (United Nations, 2022).

A large contributor to the global GHG emission by human activities is the building sector. Buildings count to the largest energy consumer in Europe and are responsible for 40% of EU's total energy consumption and 36% of EU's total energy related GHG emissions (European Commission, 2018). To reduce the environmental impact and improve the energy performance of buildings, the EU has established a directive, that will help to reach the building and renovation goals set by the *European Green Deal*. Main goals include a nearly zero-emission building stock (NZEB) by 2050, meaning a highly energy-efficient and decarbonized building stock (European Commission, 2018). Sweden introduced a climate policy framework that submits a long-term strategy in accordance with the *European Commission*, *European Green Deal* and the *Paris Agreement*, to reach the goal of a NZEB stock by 2045. As of today, the building stock in Sweden contributes highly to the country's overall emissions. In 2018 electricity and district heating production accounted for 9% (4.9 million tons of carbon dioxide equivalents), heating homes and premises for 2% (0.9 million tons of carbon dioxide equivalents) and the housing construction for 8% of total greenhouse gas emission in Sweden (Persson, 2020).

The Swedish *National Board of Housing, Building and Planning* (Boverket) has estimated that there are over 700 000 homes that need to be renovated, mainly buildings which were developed between the 1960's and 1970's within the *"One Million Program"* (Persson, 2020). The renovations of these buildings offer an opportunity to reach the national goal, by reducing the overall energy performance. Theses renovations include mainly the implementation of green-technologies, highly insulated and air tighter buildings, and installations of new systems including heat exchanger and ventilation systems (Stenberg, 2013). Not only the renovation of buildings offers an opportunity to reach the national goal, but also the construction of new buildings. In 2020 almost 39 000 new apartments have been constructed, which is 13% higher than the year before (SCB, 2020). Guidelines and thresholds for new building designs and retrofits to reach the set goals are covered by the *Swedish Building Regulation* (BBR), with limits for highest permitted primary energy consumption of a building. As a result of the new regulations, buildings in Sweden consume only half as much energy today as a typical building in the 1980's (European Commission, 2018).

Converting the Swedish building stock into more sustainable and energy efficient constructions is one pathway to mitigate the climate change by reducing or even eliminating its anthropogenic impact on the climate (Nazaroff, 2013). Some studies have analyzed the building energy saving potential for future climate conditions in Sweden. Nik (2016) analyzed the effectiveness of energy retrofitting measures and found, that an improved thermal insulation of the building envelope in combination with energy efficient windows is the most effective energy saving measure. But if mitigation strategies are not implemented with cautions to future climate it could result in negative impacts on the building and its indoor environment. A study conducted by Hosseini et al. (2022) assessed the energy performance of buildings located in Karlshamn and found that heating demand will be reduced under future climate projections, but the cooling demand can become 4-5 times higher within the next decade. His results showed that annual overheating hours can increase up to 140% in residential buildings in the south-east of Sweden, with indoor temperatures reaching up to 29.2°C. Problems with overheating mainly occur in energy efficient buildings due to two reasons: insufficient air exchange as a result of minimized infiltration and reduced heat loss rate due to the installation of thicker insulation, which are both measures to reduce the energy consumption (Fisk, 2015). Yang et al. (2021) assessed the energy performance of the European building stock, including Sweden, using future climate data, and found that extreme events of the future climate have a high impact on the energy performance and thermal comfort indoors and can increase the cooling demand with up to 28%, especially if buildings are not designed for high outdoor temperatures. The fact that Swedish residential buildings are not equipped with cooling systems increase the risk of overheating. Therefore it is crucial that energy efficient measures are installed with consideration of how they interact with the overall building design, occupancy, and future climate to adapt urban areas to climate change (Šujanová et al., 2019). One of the challenges of the future is to design buildings resilient for future climate, by reducing its energy demand and creating a safe environment for the occupants (Nik et al., 2021).

This work investigates the impact of climate change on indoor thermal comfort and further assesses the risks for human health due to temperature exposure in different climatic regions of Sweden, mainly Malmö, Stockholm and Umeå. Studies about human health impact assessment due to temperature exposure are scarce, and only few studies concentrate on the actual health outcomes due to outdoor temperature exposure in Sweden (Fonseca-Rodríguez et al., 2021; Rocklöv et al., 2014; Rocklöv and Forsberg, 2010, 2008). However, there is a gap in research when it comes to assessing the health impact due to indoor temperature exposure and how the risk can be affected under different energy-efficient measures and construction types. Analyzing the impact of indoor conditions on human health could be a good indicator for projections of risks due to future climate, considering that humans spent over 90% of their time indoors (European Commission, 2015; Spengler, 2012). A health impact assessment is conducted to project how different factors such as future environment, building characteristics and occupant behavior affect the human exposure to extreme temperatures and impact their health.

1.1 Goal and scope

The goal of this master thesis project is to investigate the indoor thermal comfort of typical residential buildings in Sweden regarding future climate and assessing the probable risks for human health due to overheating. This will be done by analysing the overheating potential of representative buildings in Sweden and evaluating the possible health outcomes due to temperature exposure

The goal of this study is to answer following research questions:

1. What is the effect of different building construction types of the Swedish building stock on the indoor overheating potential? Will the effect increase under future climate projections?
2. Does the risk of health impact differentiate between human groups shaped by individual factors?
3. Is there a difference between indoor and outdoor temperature-exposure on human health impact?
4. What is the difference between different health risk assessment methods?
5. How does the human health risk change over time?

1.2 Method

The overall method will include the following steps.

- Literature survey.
- Defining the case study

- Simulate indoor climate using IDA ICE for past and future climate. For the projections synthesized future climate weather data from Nik (2016) will be used, representing typical and extreme weather conditions for the period between 2010 to 2099.
- Analyse the output from the simulations. Different temperature-related morbidity and mortality calculations will be used, to project the changes in human health outcomes for indoor and outdoor exposure for future climate. The health impact assessment will be conducted on two different human age groups to see how the health outcomes differ between people aged 0-65 and elderly aged 65+ under future climate projections.
- Conclusions will be drawn based on literature survey and simulations.

1.3 Limitations

This study investigates the health impact of humans due to temperature exposure in three different locations of Sweden. The assessment is based on region-specific temperature functions by using functions that are based on an exposure-response relationship, which describe the relationship between temperature and daily deaths or hospitalizations, and thus quantify the health impact due to exposure. To achieve accurate predictions for each location and human group, data on daily deaths of each location was needed to assess their relation using a time-stratified design. The timeframe of this thesis did not allow to collect data on daily deaths and hospitalizations for all three cities from the Swedish National Board of Health and Welfare, because the waiting time to receive data was between 3-4 months. To increase the field of research, an exposure-response relationship based on historic data of Stockholm was used to assess the health impact for humans located in Malmö and Umeå. Therefore, presented results indicate projections on future health outcome of humans, rather than predictions.

The main goal of this study was to compare different modelling methods for health impact assessment due to indoor temperature exposure. Only one relevant model could be found, that assesses the exposure to the indoor environment, combining building physics and health. This is mainly due to the fact, that the focus on assessing human health impacts due to indoor environment is new. To increase the quality of the results, two modelling methods for health impact due to outdoor temperature are used and results of all three methods are compared to each other.

2 Background

2.1. Climate change and the human health

The increase of global average temperature can cause direct and indirect impacts on humans and their health (IPCC, 2014). Direct impacts include extreme weather events like changes in temperature and precipitation and the occurrence of heat waves, floods, droughts, and fires. Other direct impacts affect food and water supply. Indirect impacts are mainly changing in the environment and ecosystem resulting in crop failures and shifting patterns of diseases or the social responses to climate change. This chapter explains the mechanism of the human body reacting to indoor and outdoor temperature exposure.

2.1.1 Mechanism of the human body and physiological heat tolerance

The human body can gain heat in two ways: external heat gain from the environment and internal body heat generated from metabolic processes. Rapid changes in heat gain due to higher temperatures and temperature variations put the body's ability to regulate temperature at risk and can harm the human health (WHO, 2018). A natural cooling mechanism is perspiration and its evaporation from the skin, driven by cold- and warm-sensitive sensory fibers in the skin which respond to temperature changes and help the body to react to external heat gains. Cold receptors respond to temperatures between 17°C to 34°C and warm receptors to a range of 33°C to 46°C. Temperatures below 17°C cause pain to the human body, while temperatures above 43°C start to damage the skin (Šujanová et al., 2019).

The peripheral nervous system of people is responsible to regulate internal processes like heart rate, contraction, and expansion of blood vessels, to maintain a proper blood pressure and the body's reaction to stress. It basically tells the body to feel hot and/or cold and regulates the sweat production, which is a mechanism to reduce the body's core temperature. The peripheral nervous system is affected by the aging process, which is why healthy and young people can physically adapt better to changes in temperature, while the ability of elderly people decreases. With a decrease in function of the system with older age, elderly people are exposed to a higher risk of health due to heat. In addition to the physiological factors that put elderly people and people with pre-existing illnesses at risk, social factors like isolation and decreased access to support services contribute to the risk. (Spengler, 2012)

Extreme exposure to cold or heat and even small differences in seasonal average temperatures can result in illnesses, hospitalization and even deaths for humans. Extreme temperatures can worsen chronic conditions, including cardiovascular, respiratory, and cerebrovascular disease and diabetes-related conditions (WHO, 2018). Low temperatures (< 18°C) can cause hypothermia, thickening of blood, hypertension, respiratory stress (< 16°C) and cardiovascular stress (< 12°C) (Ormandy and Ezratty, 2016). With a body core temperature above 38°C, humans physical and cognitive functions are impaired, causing heat exhaustion. If the body temperature exceeds 40.6°C the risk of; organ damage, loss of consciousness and death increase (Dokken, 2018). Heat-related health impacts can occur directly after exposure or after a few days, other than cold related health impacts (Ormandy and Ezratty, 2016). Another difference between heat and cold effects on humans, is that high temperature effects vary depending on local and regional climate conditions. An optimum temperature from the health perspective (the maximum temperature threshold with lowest number of deaths) is dependent on multiple factors and thus different when globally considered. While the optimum temperature in 14°C in Finland, is it around 20°C in London and around 25°C in Athens (Swedish Commission, 2007).

2.1.2 Extreme outdoor temperatures

According to the World Health Organization (WHO) the number of people exposed to heat due to climate change is increasing, with heat waves being the highest cause of weather-related deaths, responsible for more deaths than other extreme weather events (WHO, 2018a). Between 2000 and 2016 the number of people exposed to heat waves increased by 125 million and the heat wave of 2003 in Europe resulted in 70 000 excess deaths, of which about 80% were people over 75 years old (WHO, 2018a). The heat wave in 2018 caused 635 more deaths in Sweden. This accounts for a 8.2% increase in mortality during the heat wave period between the 2nd July to 5th of August compared to the same period in 2017 (Åström et al., 2019).

Several researchers conducted studies, that link extreme temperatures (cold or warm) to negative health impacts and an increased number of deaths. The relationship between weather and human deaths has been widely studied and results indicate a geographical dependency. The exposure-response relationship of humans is often J- or U-shaped, with a minimum mortality temperature (MMT) on the bottom, at which the mortality is the lowest. The mortality increases with higher/ lower temperatures, creating a J- or U-shaped graph visualizing the relationship dependent on the location. While the MMT is about 11-12°C in Scandinavian countries, it is 27°C in Miami, Florida. (Ye et al., 2012)

Many studies assessed the relation between temperature and health specifically in Sweden. A recent study by Åström et al. (2020) assessed the potential impact on mortality due to higher frequency of heat waves in 14 municipalities in Sweden. Results indicated an increase in mortality on a national level of 10% in all cause and 15% in CHD (coronary heart diseases). His study is based on the daily maximum temperatures and mortality for the five warmest months between 1990 and 2014. Another study by Åström et al.(2016) analyzed the evolution of the minimum mortality temperature (MMT) in Stockholm between 1901 and 2009. The MMT describes a temperature threshold, at which the mortality is at a minimum. The study suggests that an autonomous human adaptation can occur, mainly based on the results that the absolute and relative MMT increased in Stockholm as a result of increasing global mean surface temperature. Rocklöv and Forsberg (2008) analyzed the effect of temperature on health in the Stockholm region between 1998 and 2003. The main findings include that the natural mortality in Stockholm had a seasonal pattern, which is higher in winter months. Heatwaves increase the daily mortality of 3.1% – 7.7%, depending on the threshold and mainly caused by cardiovascular and respiratory diseases. These results indicate that health risks associated with heat and heat waves are of higher public threat than cold effects, because the northern population has not been able to adapt to the heat (Rocklöv and Forsberg, 2008). A more recent study by Rocklöv et al. (2014) assessed the relation between mortality and hot and cold temperatures according to individual factors and history of previous in-hospital care. Results indicated that mortality increased more in the elderly when temperature increase gradually, while heat wave events had a higher impact on mortality among the population less than age 65. Heat wave events had a significant impact on people aged 65 and higher with a mental health condition or pre-existing cardiovascular disease. Gradually decreasing temperatures and the duration of cold waves had the highest effect on the elderly population. In another study Rocklöv and Forsberg (2010) analyzed the effect of high ambient temperatures on people above an age of 65 years in three regions of Sweden. The study found that the heat susceptibility for people aged 65+ is similar in all three regions, with cold related mortality in summer being the highest in the south, probably due to the adaptation. An important observation here is that most studies regarding temperature related mortality in Sweden are based on past climate data. The possible increase of risk due to future climate has not been widely studied for Sweden and as the above-mentioned authors suggest, there is a need to investigate the cold and heat related mortality for future climate.

There are studies available that project future heat-related mortality regarding different climate change scenarios. Baccini et al. (2011) studied the influence of increasing ambient temperature by 2090-2099 relative to 1980-1999 on daily mortality in 15 European cities and found that the impact will increase in the future due to increase of mean ambient temperature and the frequency, intensity, and duration of heat waves. Highest impact is expected for elderly people (over 75 years) and on Mediterranean cities (Barcelona, Rome, Valencia). The EuroHEAT project studied the impact of heat waves on mortality in 9 European cities and found similar results to the study by Baccini et al. (2011). EuroHEAT found that the effect of heat waves was geographical heterogony among cities and the mortality during heat waves has a higher impact in Mediterranean countries (21.8% for total mortality) than in the northern parts of Europe (12.4% for total mortality) (D'Ippoliti et al., 2010). Higher effects were observed for respiratory diseases and for elderly woman (aged 75-84). Gasparrini et al. (2017) showed in his study that on average, a net increase in temperature-related excess mortality is to be expected under high-emission scenarios, with geographical differences. In northern Europe, east Asia, and Australia (with temperate climates) the net temperature-related excess mortality would induce a null effect, accounting for lower intense warming in the future and the large decrease in cold-related deaths. In contrast to that warmer region like central and south America or Europe and southeast Asia will experience a strong increase, highlighting the fact that negative health impacts of climate change would affect warmer and poorer regions of the world stronger (IPCC, 2014; WHO, 2018a).

Main results of available studies indicate that heat-related summer mortality will increase, and winter mortality will decrease in the future. Demographic changes as well as human acclimatization in the future are neglected in most of the studies, which could cause an under-/ overestimation of the results. Taking an aging population into account, which is more susceptible temperature extremes, could increase the results. In contrast, accounting for human acclimatization to climate change could reduce the results (Huang et al., 2011). Other causes for false/ wrong projections of the future temperature-mortality could be due to differences in city sizes, the urban heat effect, population age, ground-level ozone, cultural differences, and adaptations to high temperatures (air conditioning, human behavior etc.) (Swedish Commission, 2007).

2.1.3 Extreme indoor temperatures

Most of the studies discussed above focus on human health impacts from heat mainly due to heat wave events, which are found to cause a rapid increase in mortality. The impact analysis of indoor temperature exposure and human health is scarce due to its complexity. There are four factors influencing the indoor environmental quality: 1) macroenvironment including outdoor pollution, climate conditions and radon emission; 2) building infrastructure including heating, ventilation, air conditioning (HVAC) systems, electric and plumbing system, materials, and furnishings, building design and characteristics and occupant activity; 3) health state and 4) human perception (Fisk, 2015). Analyzing the impact of indoor conditions on human health could be a good indicator for projections of risks due to future climate, considering that humans spent over 90% of their time indoors, of which approximately 70% is spent in residential buildings (European Commission, 2015; Spengler, 2012).

The Institute of Medicine (IOM) summarized the potential consequences of climate change on the indoor environment and the risks for human comfort and health (Fisk, 2015). Table 1 presents the potential consequences for human comfort and health due to three different pathways: 1) due to outdoor environment conditions, 2) climate change adaptation and 3) climate change mitigation measures.

Table 1: Potential consequences for human indoor comfort and health due to climate change; three possible pathways: due to changes in outdoor environment, climate change adaptation and mitigation; adapted from Fisk (2015).

		Effects on indoor environment	**Potential effects on comfort and health**
Outdoor environment conditions	Extreme temperatures/ heat waves	Periods of high temperatures	Discomfort, heat stress, hospitalization, deaths
	Extreme weather events/ hurricanes, floods	Dampness and mold	Respiratory health effects
	Wildfires, outdoor air particles	Periods of high concentrations of airborne particles	Respiratory and cardiovascular health effects; hospitalizations; deaths
	Ozone	Higher indoor ozone	Respiratory health effects; hospitalizations; deaths
	Pollens	High indoor pollen allergens	Allergies; asthma
Climate change adaptation	More air conditioning	Avoidance of high temperature and humidity; Lower ozone and pollen allergens concentration, microbial pollutants from air conditioning	Improved thermal comfort; increase/ decrease in respiratory health effects
Climate Change mitigation	Higher energy efficient buildings	Improved/ worsened thermal comfort conditions; increased overheating potential if no air conditioning available; increase/ decrease in indoor air pollutants	Improved thermal comfort; Increase/ decrease in respiratory health effects; Sick-Building-Syndrome; Chronic health effects

Changes in the outdoor environment due to climate change are potential risks for human health due to extreme temperature exposure as discussed in the previous chapter. But extreme outdoor weather conditions can worsen the indoor climate conditions and consequently create a risk for the human health. The human health is at risk indoors due to mold and dampness, which will increase due to future climate is if no adequate measures are done (Nik et al., 2012; Sivolova and Gremmelspacher, 2019). Due to worse indoor air quality resulting from changes in indoor air pollution concentrations due to different outdoor air pollutants, wrong/ false ventilation rate or air-conditioner use and higher ozone exposure (Nazaroff, 2013). Due to higher outdoor temperatures, which increase the indoor temperatures and thus the potential of overheating of buildings (Hosseini et al., 2022; Lundgren Kownacki et al., 2019; Mavrogianni et al., 2012; Simson et al., 2015; Spengler, 2012; Yang et al., 2021). Therefore, people indoors are exposed to discomfort and heat stress, which can result in respiratory and cardiovascular illness and eventually end in hospitalizations or deaths.

Climate change adaptation and mitigation measures are two other pathways, leading to consequences on human thermal comfort and health. The use of air conditioning as an active adaptation measure could reduce extreme temperatures and humidity, leading to improvement of thermal comfort, but cause increasing rate of microbial pollutants and thus increase respiratory health effects (Fisk, 2015). Mitigation measures, such as energy efficiency of buildings, can have negative consequences on the indoor environment due to higher airtightness of the building envelope, which is required to reduce the heat losses and thus increase energy efficiency. In return the lower air infiltration causes poor indoor air quality due to lack of exchanging the stale indoor air with fresh outdoor air (NHBC Foundation, 2018). Another consequence of energy-efficient buildings is that the high airtightness is increasing the indoor temperatures, leading to overheating potential. Mavrogianni et al. (2014) showed in their study, that the wall and roof insulation level have a considerable impact on indoor temperatures and retrofit measures with the increase in insulation material increase the daytime living room temperatures. Higher overheating can lead to increase in respiratory health effects, chronic health effects, sick building syndrome and reduction of performance. Šujanová et al. (2019) found out that temperatures between 25°C – 35°C decrease the overall human performance, while lower temperatures between 21°C – 25°C showed no impact.

The WHO conducted a research review on potential health outcomes due to high indoor temperatures. Main findings state that no direct link between health and high indoor temperatures could be identified, meaning that there is no evidence that people living in housing with temperatures above 24°C have worse health outcomes than people living in housing below that threshold. Despite these results, the WHO underlines the importance of keeping the indoor temperature below the threshold, which can have beneficial health effects for vulnerable human groups like elderly, infants, sick and disabled (WHO, 2018b). In contrast to the WHO findings, Taylor et al. (2018,2021) conducted several studies on projections of indoor temperature-related mortality in the UK regarding future climate, linking high indoor temperatures to potential risks for human health. In a study projecting the impacts of housing on the mortality in London, Taylor et al. (2021) indicate that cold-related mortality will decrease in the future while heat-related mortality will increase if no changes in buildings are accounted for. If energy efficient retrofits are considered, a reduction of cold related deaths by annually 73 per million in 2030's and 168-174 per million by 2050's is expected, while annual heat related death will increase by around 1 death per million by 2050's. These results indicate that future climate will lower the cold-related deaths but increase the heat-related deaths. In another study Taylor et al. (2018) analyzed the effects of built environment adaptation to heat exposure and mortality during hot weather and found, that summertime heat mortality increases 3-4% in a full energy efficient retrofit and decreases when using external shutters by 37-43%. This results highlight that retrofit measures can reduce the risk for human health due to future climate change, if applied adequately. The studies conducted by Taylor et al. (2018, 2021) underline the fact that more research is needed in the field of climate change adaptation and mitigation measures in order to understand the possible risks and limitations for the human health. Indoor overheating, as a result of climate change, increaes the risk of human mortality and depends on the interaction between occupant's behaviour, building location and building characterisitcs. Understanding the factors and their interaction is crucial to mititgate climate change and reduce the risk of overheating (Bundle et al., 2018).

Yang et al. (2021) studied the impacts of climate change on the energy performance and thermal comfort of the European residential building stock and found that climate change will drastically affect the future energy demands of buildings. The cooling need for buildings will increase with an average of 28% in the future, while the heating need will decrease with an average of 16%. Cooling need will mainly increase due to adaptation to warmer temperatures and the reduction of overheating within the building. Nik and Sasic Kalagasidis (2013) conducted a similar study on the building stock in Stockholm and found that the heating energy demand will decrease with about 30% until the year 2100, while the cooling demand will increase. Their study also showed that the heating and cooling demand can differ with up to 30% and more comparing different future climate scenarios, highlighting the fact that future climate uncertainties can affect the estimated energy demands. Dodoo et al. (2014) analyzed the potential of overheating and increase in energy use regarding future climate of energy efficient building constructions and passive houses in Växjö, Sweden. Results indicate an increased risk of overheating, increased cooling demand and decreased heating demand under the representative concentration pathways (RCP) 4.5 and 8.5 scenarios. The author highlighted that the changes are proportionally more significant for the passive compared to the conventional building, with increase in cooling energy need of 39-49% and 33-42% respectively. Another recent study assessed the sustainable energy transition of Swedish cities, in regard of future climate and urbanization (Hosseini et al., 2022). Results highlight the importance of using future climate data on a microclimate scale, to estimate the impacts of climate change and microclimate variations accordingly. Results indicated that annual cooling demand increases 4 to 5 times in the next century. Hosseini et al. (2022) highlighted that the lack of cooling systems can cause continuous indoor temperatures of 26°C and higher and overheating hours will increase up to 140% in the future. Published research regarding future energy performance and risk of overheating of buildings indicate the importance of accounting for future climate when designing buildings to adapt and mitigate accordingly, with no reverse effects on human health and the buildings energy performance.

2.2 Indoor climate – human thermal comfort

With people spending up to 90% of their time indoors, researchers assume that the indoor climate will have a significant impact on the human health (Spengler, 2012). Many factors are included when adressing indoor climate, which are differently perceived by the people living indoors and depend on many individual and environmental factors. Indoor climate includes the thermal, hygienic, light, and sound comfort. This study is concentrating only on the thermal comfort and health risks caused by extreme temperatures. In the following, the term thermal comfort is defined, factors affecting the perception of humans are listed and a widely used method to analyze thermal comfort in presented.

2.2.1 Thermal comfort – definition

According to the definition by the Swedish National Board of Housing (Boverket, 2022) and European Standard ISO 7730 (SIS, 2006), *thermal comfort* means how a space is experienced in terms of temperature and draft. Thermal comfort is achieved, when the thermal balance of a human's body is in balance as a whole and the thermal heat production in the body is equal to the losses of heat to the environment. This balance is influenced by individual factors, like activity and clothing, and environmental factors, including air temperature, the radiation of heat from surrounding surfaces, air velocity and humidity. Building characteristics such as thermal insulation capacity of materials, window sizes, heating systems and ventilation systems affect the indoor climate. Thermal discomfort occurs if the human thermal regulation is out of balance. Temperature requirements to maintain thermal comfort include a minimum of 21°C in spaces for residential purposes. In spaces for elderly people the requirement is a minimum of 22°C (Boverket, 2022). The maximum temperature threshold is a recommendation of the Swedish Public Health Agency with 24°C in winter and 26°C in summer (SVEBY 1.0, 2012).

2.2.2 Factors affecting indoor thermal comfort

Building regulations usually do not define a temperature threshold to maintain thermal comfort. The Swedish Public Health Agency set recommendations, which are not based on research, and are therefore of no meaning on when adverse health effects occur. This is mainly due to the fact, that the perception of temperature depends on several factors, which makes it impossible to satisfy every human being with the same temperature (Göransson and Götharson, 2015). A human's individual perceptions on overall satisfaction is influenced by environmental, building, and individual factors. These factors depend on each other as figure 1 shows.

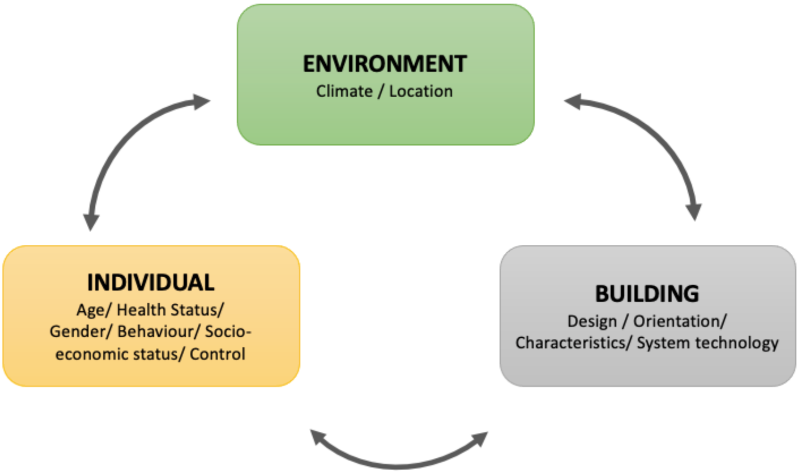


Figure 1: Three factors influencing human thermal satisfaction indoors; adapted from (Šujanová et al., 2019).

Environmental factors include the conditions of the regional and local climate, and their impact depends on the acclimatization potential of the population. This results in the fact that a discomfort level varies from human to human and depends on a personal ability of adaptation, resulting in different thresholds at which thermal discomfort starts and temperature can cause a dangerous condition (Šujanová et al., 2019). Population of cities in colder climates has a lower threshold, than people living in warmer climates. Ormandy and Ezratty (2016) found in a study that thermal discomfort starts at 22°C and 26°C are perceived as too hot for people living in Finland, which are perceived as normal for people living in warmer climates. Adaptation to temperature has a high influence on the heat-related mortality and is different for populations of different climates. While the threshold for minimal indoor risk temperature for heat related health effects is 22-23°C in London, it is about 30°C in Thailand (WHO, 2018b). Another factor influencing the mortality is the timing of heat waves. If heat waves occur early in the year, they have a higher impact because people did not have the chance to adapt to higher temperatures (WHO, 2018b). Researchers assume that climate change with its increasing temperatures, might itself be a factor for acclimatization (Taylor et al., 2021).

A building can influence the thermal satisfaction of a human through location, orientation, the elevation of the living space, the effectiveness of heating and cooling and the building characteristics (Anderson et al., 2013). If the building is in a dense urban area, the Urban Heat Island (UHI) effect can influence the indoor environment. The UHI effect is a term that describes the variation between urban and rural temperatures due to atmospheric and surface impacts, such as reflected or emitted heat from people, vehicles, buildings, and roads. It is caused by rapid urbanization and results in high urban temperatures (Anderson et al., 2013). Air temperatures between urban and rural areas can differ with up to 16% (Javanroodi and Nik, 2020). Studies showed, that the UHI can contribute to 21% of heat-related mortality (Taylor et al., 2018b). The orientation and elevation of buildings are factors that influence the indoor environment. Apartments oriented to the south with large window areas are more susceptible to excess heat than apartments on the ground floor oriented to the north (Ormandy and Ezratty, 2016). The year of construction and the specific building design of that period influence the indoor environment. Zalejska-Jonsson and Wilhelmsson (2013) studied Swedish dwellings constructed in different periods and their impact on the perceived indoor environment and found, that different indoor environmental problems and their impact on occupant's overall satisfaction depend on the construction year and design. Buildings built before the 1960's have main problems with draught while buildings built between 1961 and 1975 have problems with too low temperatures. In general, they concluded that buildings constructed before 1975 showed high sensitivity with thermal comfort problems, mainly due to the fact, that these buildings were built with low or no insulation and low energy efficient windows. In contrast to that, recently constructed buildings (built between 1996-2005) showed main problems with air quality, in particular unpleasant smell, and stuffy air. Energy efficient measures to reduce the heating demand of a building like higher insulation thickness and increased airtightness have an impact on the indoor temperatures. A study conducted by Mavrogianni et al. (2012) analyzed how energy efficient buildings impact the indoor environment in London. Their results showed that higher wall insulation increases on average the indoor temperatures. In contrast to that roof insulation and higher efficient windows reduced the indoor temperatures on average. Increased airtightness of a building envelope increases the indoor temperatures, because it limits the heat loss via infiltration and trapping heat from internal and solar gains inside (Ormandy and Ezratty, 2016).

The third factor which is influencing the thermal perception of humans are individual factors. They depend highly on the health status of an individual, age, gender and socio-economic status as well as behavior and awareness (Ormandy and Ezratty, 2016). Older people (65+) and younger (up to 5 years) are of higher risk of thermal discomfort due to their physical state and not well functioning or immature thermoregulation system. They are more susceptible to suffer from indoor thermal discomfort because they spent more time at home than other age groups. The exposure to extreme temperatures indoors can have a high impact on their health, especially if they have pre-existing illnesses, like cardiovascular or respiratory diseases (Vardoulakis et al., 2015; Bundle et al., 2018). Older people have a lower awareness of changes in thermal conditions of their immediate environment, increasing the risk of thermal discomfort (Yi et al., 2022).

2.3 Fanger's indoor thermal comfort incidents

To achieve thermal satisfaction, the body's heat production and loss (to the environment) should be in balance. A widely used method to assess thermal comfort is the Predicted Mean Vote (PMV) method, which was established by the Danish indoor climate researcher Fanger and is based on the thermal balance to achieve thermal satisfaction (Göransson and Götharson, 2015). The PMV index calculates the predicted mean value of votes of a large group of people that are exposed to the same environment. The calculation is based on six factors, including the metabolic rate, clothing insulation, air temperature, relative humidity, air velocity and mean radiant temperature. The PMV index can be determined for an average person using a 7-point scale, that is presented in table 2. A person feels thermally neutral at a PMV of 0, with a tolerance of +/- 0.5 (Hoof and Hensen(2006); SIS (2006)).

Table 2: Seven-point scale of the PMV method to assess human thermal comfort (SIS, 2006)

PMV index	**Thermal perception**
+3	Hot
+2	Warm
+1	Slightly warm
0	Neutral
-1	Slightly cool
-2	Cool
-3	Cold

With the PMV the percentage of people that feel thermally dissatisfied can be determined. The predicted percentage of dissatisfied (PPD) index is used for the estimation of percentage of people that feel too warm or too cold in their surrounding indoor environment. Figure 2 shows the relation between PMV and PPD. Maximum 95% of the people in a room can feel thermally satisfied with the indoor climate, which is due to individual factors, including the metabolic rate and clothing, that can affect the perception of a human (SIS, 2006).

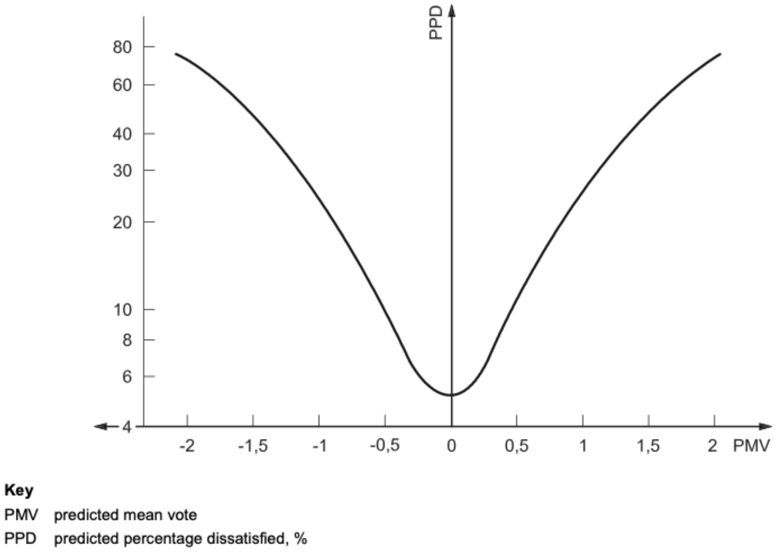


Figure 2: PPD as a function of PMV (SIS, 2006)

The international standard EN ISO 7730 and ASHRAE 55 adapted the Fanger's comfort index to predict the number of people that are dissatisfied with indoor climate conditions. Even though it is widely used, the reliability of this method for different age groups is being questioned amongst researchers. This is based on the fact, that the method was developed under steady-state conditions in a climate chamber and the results are based on about 1300 young adults, while the application of this method for older people was evaluated with 128 elderly people (Hoof and Hensen, 2006). Yi et al. (2022) assessed in a study the reliability of the PMV method for older people and found, that by adjusting the two individual factors, metabolic rate, and clothing insulation, the method is applicable for elderly people. But adjustments must be conducted with cautious, because the PMV is particularly sensitive to metabolism and clothing insulation and inaccurate assumptions can lead to over/ underestimations of the thermal comfort assessment (Hoof and Hensen, 2006).

3 Method

The methods used to assess the impacts of climate change on the probable risks for human health in the typical Swedish residential building are discussed in this chapter. The study consists of three steps, where the first step consists of the energy modelling of a representative building of the Swedish housing stock and its verification using past climate data. Based on the verified model, the human health impact in terms of thermal comfort, morbidity and mortality is assessed using different methods and synthesized future climate data including typical and extreme conditions in the second step. In the third step, the results of the different methods are being systematically compared to draw conclusions on the projections of how future climate will impact the human health due to exposure to indoor and outdoor temperatures. The workflow is represented in figure 3. A representative building of the Swedish residential building stock was chosen, and three building constructions were analyzed including: typical building, retrofitted and newly built.

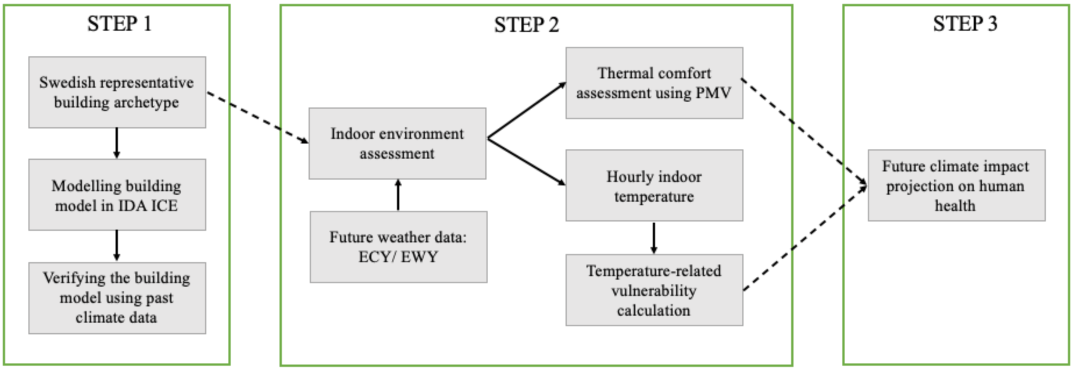


Figure 3: Workflow of the study

3.1 Case Study

A multi-family house (MFH) was chosen as the representative building type for the Swedish residential building stock, accounting for 49% of all Swedish households in 2020, followed by one/two apartment buildings with 40 % (SCB, 2021). The building characteristics of a typical Swedish MFH were retrieved from the TABULA webtool (https://webtool.building-typology.eu), which is a database that provides building typologies of a national building stock. The database collected information about the Swedish residential building stock from Mälardalens University. The webtool represents typical single- and multi-family homes within the Swedish building stock constructed between the 1960's up to 2005. Building typologies for five different MFH constructions are available in the webtool. This study concentrates on the MFH constructed between 1961 and 1975, mainly buildings constructed within the "Million Homes Program", which account for 40% of the total MFH stock in Sweden (Slaug et al., 2020). According to the Swedish Building Regulations BBR there are over 700 000 buildings, mainly from the "Million Homes Program" era, that need to be renovated to reach the Swedish target of a NZEB till 2045 (Persson, 2020). Physical characteristics of a typical MFH (constructed between 1961 and 1975) were provided by the webtool and helped to construct a building energy model. Typical characteristics include three story's, band windows and flat roofs (Lindahl and Sacco, 2016).The characteristics of the MFH retrieved from the webtool can be seen in table 3.

Table 3: Typical building characteristics from a MFH of the Swedish building stock, retrieved from TABULA webtool

Building characteristic/ Area	**Value**
Roof	470 m^2
Heated floor	1420 m^2
External wall	560 m^2
Total windows	180 m^2
Number of stories	3
Story height	2.50 m
Volume	3500 m^3

Three different construction types of the representative MFH are analyzed: original state (building A), retrofit design (building B) and newly built (building C). Different construction types are assessed, to draw conclusions of how the future climate in combination with different construction types available in the Swedish housing stock affect the indoor thermal comfort and human health. Building A represents the original state of a MFH built between 1961-1975, which represents as of today over one third of Sweden's present building stock (Persson, 2020). Building B represents a retrofit of building A, whereas retrofits are the most used strategy to improve the energy performance of a building. Most retrofit measures of a MFH from the million program era include the change of energy carries from fuel to district heating (Bergström and Save-Öfverholm, 2011) and changes of the building envelope (adding insulation or exchanging windows) to reduce the thermal losses through the envelope and thus reduce energy consumption of a building (Lindahl and Sacco, 2016). TABULA provides characteristic properties for each building construction for the original state of the building and a typical retrofit (TABULA, 2016). For the newly built design, the building model was constructed in accordance with the Swedish Building Regulation (BBR 29), where the average heat transfer coefficient U_m was not to exceed 0.4 W/(m^2K) (Boverket, 2020). The calculation of U_m can be seen in appendix 8.1. Table 4 shows the properties of the three constructions and all values, if not marked, were retrieved from the webtool (TABULA, 2016).

Table 4: Heat transfer values for each construction type for building A, B, C

Construction Type	**U-Value (W/m^{2}K)**		
	Typical building (Building A)	**Retrofit design (Building B)**	**New design (Building C)**
Roof	0.20	0.10	0.08 [1]
Wall external	0.41	0.24	0.10 [2]
Slab on the ground	0.26	0.20	0.10 [3]
Window	2.22	0.90	0.90
U$_m$	1.02	0.63	0.31

1) https://www.isover.se/solutions/lt71-plant-papptak-trastomme-42-db
2) https://www.isover.se/solutions/yt11-traregelvagg-med-ventilerad-trafasad-rei30-50-55-db
3) https://www.isover.se/solutions/gb06-sockel-med-dubbla-l-element

The exterior wall construction of buildings A and B consists of prefabricated light weight concrete sandwich elements with a polystyrene core, as seen in table 5. The exterior wall of building C consists of a wooden frame construction. Since the building construction consist of different materials, mainly wood, insulation, and concrete, they have a different thermal mass. The thermal mass of a construction and it's building materials is describing the capacity of the material to store, absorb and release heat (Sala Lizarraga and Picallo-Perez, 2020). A bigger thermal mass can provide a larger inertia against temperature fluctuations. Table 6 shows the thermal properties and thermal mass of the two light-weight concrete construction (building A and B) and the wooden-frame construction (building C), which were calculated thermal mass of each construction. The thermal mass was calculated according to equation 1.

$$Q = m * c_p * \Delta T \ (J/K) \tag{1}$$

Where Q is the thermal mass, m is the mass of the material, c_p is the heat capacity of the material under constant pressure and ΔT is the temperature difference, which is 1K in this case.

Table 5: Exterior wall construction of the three different buildings A, B and C. Exterior side is to the right.

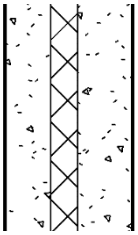
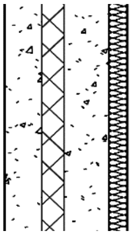
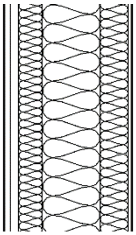
Typical building (Building A)	**Retrofit design (Building B)**	**New design (Building C)**
		

Table 6: Thermal properties of building material in exterior wall construction of building A, B, C and the calculated thermal mass for 1m² of layer and 1 K temperature difference

	Layer (from inside to outside)	**thickness (m)**	**c_p (J/g*K)**	**m (kg/m3)**	**Q (J/K)**	**Q_{total} (J/K)**
Building A (original)	concrete	0.12	1050	2400	302	
	EPS	0.08	1100	29	3	
	concrete	0.10	1050	2400	252	557
Building B (retrofit)	concrete	0.12	1050	2400	302	
	EPS	0.08	1100	29	3	
	concrete	0.10	1050	2400	252	
	insulation	0.05	840	60	3	559
Building C (new)	glass wool	0.08	840	60	4	
	glass wool	0.20	840	60	10	
	glass wool	0.10	840	60	5	
	wood (12%)	0.04	1650	440	32	51

A high thermal mass can reduce the temperature fluctuations of a day by absorbing heat in the material and releasing it once the surrounding environment cooled down, therefore balancing indoor temperature and reducing energy use (Sala Lizarraga and Picallo-Perez, 2020). Table 6 represents the thermal mass of all three construction, highlighting the fact that building A and B have an almost 10 times higher thermal mass compared to building C.

3.2 Locations and climate zones

The study was conducted using climate data for three different cities in Sweden, representing climate zones in the south, middle and north represented respectively by the cities Malmö (Skåne), Stockholm (Stockholm) and Umeå (Våsterbotten). Sweden extends through the latitudes 55°N - 69°N resulting in different climatic and environmental conditions throughout the country (Fonseca-Rodríguez et al., 2021). According to the Köppen-Geiger climate classification system, the climate in the south of Sweden is oceanic, the center humid continental and the north subarctic (World Bank Group, 2021). The selected cities represent three of the four climatic regions in Sweden, which are defined by the Swedish building regulation BBR to adjust the requirements for a building due to regional variations (Boverket, 2020).

Figure 4: Geographical location of the case studies

Main criteria for the selected locations were the population size, which increases the size of results. No significant location was found in climate zone 2, therefore this zone is neglected in this study. Table 7 represents the population per city/ county by age of the selected locations. With a total of 4 092 127 people, the three regions cover almost 40% of the total population in Sweden of 10 452 326 (SCB, 2022).

Table 7: Swedish Population in December 2021 divided in two age groups, below and above 65 years

	< 65	**65 +**	**total**
Malmö	1 126 254	276 171	1 402 425
Stockholm	2 023 342	391 797	2 415 139
Umeå	215 311	59 252	274 563

Sweden is expected to have warmer and wetter winters and warmer and drier summers with an increase in average annual temperature of 6°C by the 2080's (SMHI, 2015). Malmö and Stockholm located in the south of Sweden, with annual average temperatures of the warmest month July of 18.0°C (climate data, 2022), are therefore more susceptible of experiencing warmer and extreme temperatures due to climate change than the north.

3.3 Building energy modelling and verification

The building energy model was constructed within the program IDA ICE, which is a commonly used dynamic multi-zone simulation application developed by EQUA, to assess the energy consumption and thermal indoor climate of a building (EQUA, 2022). Figure 5 shows the building model of the MFH representative for the Swedish housing stock as generated by IDA ICE.

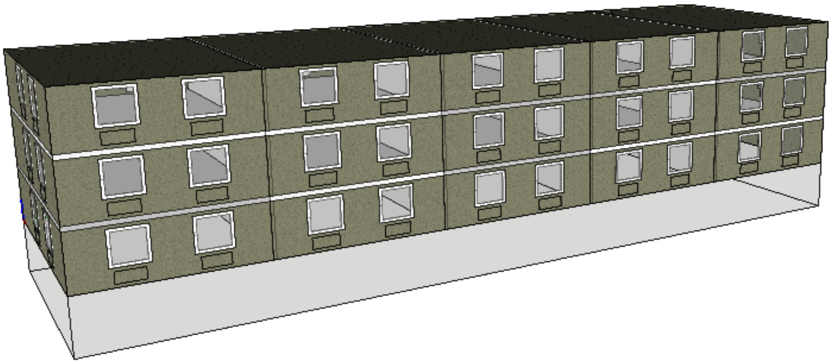


Figure 5: Model of MFH in IDA ICE

The model was constructed in IDA ICE using the building dimensions and input parameters as described in table 3 and table 4. The buildings are equipped with different heating and ventilation systems, depending on the year of construction. The systems of building A and B are well described in the webtool (TABULA, 2016), for building C common used building systems are used. Building A was constructed when buildings were dependent on cheap electricity and were built before the oil crisis (1973-1974) (Stenberg, 2013). Therefore, building A is equipped with a heating system that runs by fuel/oil, with an energy expenditure coefficient[1] of 1.11. Building B is connected to the district heating (DH) with an energy expenditure coefficient of 1.33. Building A and B are equipped with a natural ventilation system and the infiltration rate of the building envelope is 0.4 ACH (air changes per hour) and 0.2 ACH at 50 Pa respectively. The heating system for building C, the new design, was chosen to district heating with a coefficient of performance (COP) of 3 (Swedish Energy Agency, 2015). The utilization of district heating is common in Swedish residential buildings, with 93% of all dwellings in MFH being connected to DH in 2014 (Werner, 2017). For more homogenous cases, building C is designed with natural

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[1] The energy expenditure coefficient is defined as the ratio of delivered energy/heat use to produced energy/heat use (TABULA, 2013)

ventilation. Heating set point was set to 21°C and since most Swedish buildings is not equipped with air conditioning, no cooling set point was assigned.

The energy performance of buildings is highly influenced by surrounding conditions and parameters of the microclimate. In this study a simplified model was used, the influences of surrounding buildings and vegetation are being neglected. The fact of neglecting surrounding conditions causes a limitation of the results, especially because vegetation and its varying density, solar gains and reflectivity, air temperature and wind speed and shading through surrounding buildings within the urban context influence the building energy performance and thus the thermal comfort highly (Hosseini et al., 2022).

The three models were verified using reference heating demand values from TABULA (for building A and B) and BBR 29 (for building C) using weather data for Skåne, Stockholm and Umeå. The reference values for the different locations are listed in table 8 below. BBR 29 requires a maximum primary energy use of 75 kWh/m^2 (primary energy number) for MFH. The primary energy number is specific for each location and is adjusted using geographical factors set by BBR. The calculation of the specific heating demand for each location using the adjusting-factors can be seen in appendix 8.2. The TABULA webtool is based on the old division of Sweden, where Malmö and Stockholm are in the same climate zone. Therefore, Building A and B in Malmö and Stockholm have the same heating demand. Values for building C are obtained from the Swedish Building Regulation BBR, which accounts for the climate adjustment factor, resulting in different heating demands for these two cities.

Table 8: Heating energy demand for the three buildings in three climate zones of Sweden

	Heating energy demand (kWh/m^2)		
	Skåne	Stockholm	Västerbotten
Building A	115	115	172
Building B	84	84	131
Building C	66	82	106

3.4 Climate data sets

In this study, past and future climate datasets were used. The building model was verified using the past climate data, while the future climate was used to project the human health impact due to temperature exposure. In the following chapter both climate data will be presented.

3.4.1 Past climate data

The past climate data sets used in this study to verify the building model are standard EnergyPlus Weather (EPW) files from the ASHRAE database of International Weather for Energy Calculations v 2.0 (IWEC 2), which is one of four climate files available for IDA

ICE, and was found on the EQUA Climate Data Download center (EQUA, 2013). The climate files from IWEC 2 are derived from meteorological reports of weather stations around the world and are collected in the Integrated Surface Hourly (ISH) data base of the National Climatic Data Center (NCDC). The ISH database contains real data of wind speed and direction, sky cover, visibility, dry-bulb temperature, dew-point temperature, atmospheric pressure, liquid precipitation, and present weather for the past 25 years. The data base uses total solar radiation values that were calculated with the help of empirical models (AHSRAE, 2018). These weather files of IWEC 2 are Typical Meteorological Year (TMY) data sets, which represents the hourly meteorological measurements over several years. For each month of the TMY, data from the year that was considered as most typical for that month over the total period was chosen (European Energy Efficiency Platform (E3P), 2016). Figure 7 represents the TMY dry-bulb temperature for the three cities of interest. The period of meteorological measurements is for each city individual: Malmö 2004 – 2018, Stockholm 2002 – 2019 and Umeå 2004 – 2018, the year of record for each month can be read in appendix 8.3.

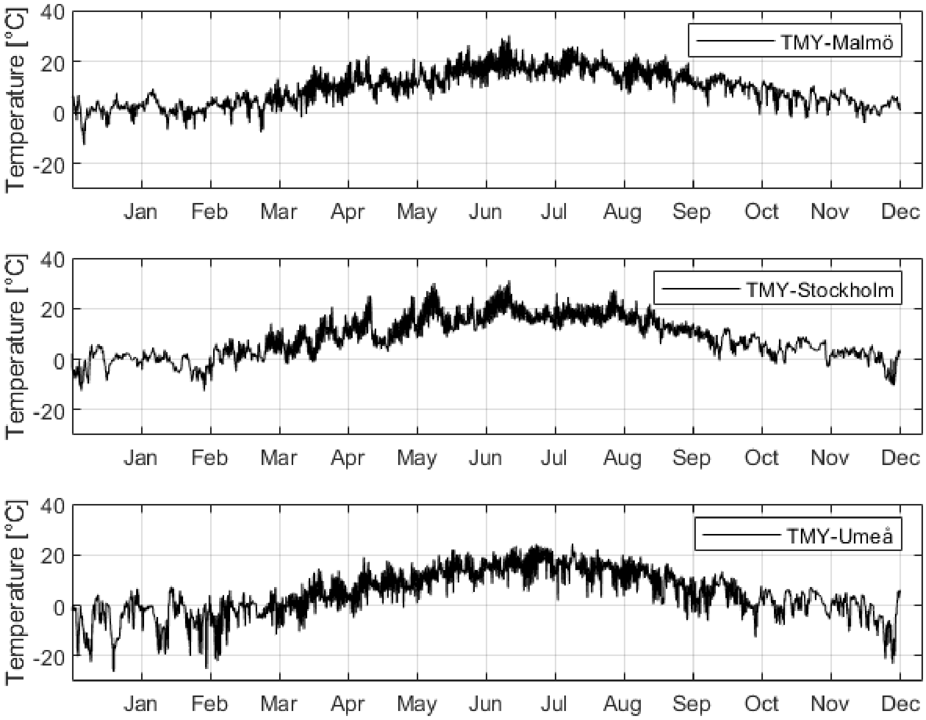

Figure 6: Dry bulb temperature of the TMY for Malmö, Stockholm and Umeå

Malmö's coldest month is February with an average temperature of 0°C, while the warmest month is July with an average temperature of 16.2°C. Highest measured temperature is 30.3 in July and lowest is -12.9 in January. Stockholm shows similar results, with an average of -2.5°C and 17.7°C for the months February and July respectively. Highest measured temperature is 31.2°C in July and lowest is -12.4 in February. In Umeå, the coldest month is February with an average of -6°C, while the coldest temperature was measured as -26.1°C in January. The warmest month on average is July with 15.9°C and the highest temperature was measure din May with 24.4°C. Yearly mean average temperatures are 8.2°C, 7.3°C and 3.9°C for Malmö, Stockholm and Umeå respectively.

3.4.2 Future climate data

To assess the impact of climate change on the indoor thermal comfort and human health, many scenarios must be considered to account for all future climate scenarios and modelling uncertainties. Global Climate Models (GCMs) are used to predict a climatic behavior in the future, which predict the degree of climate change caused by natural variability, human activity, or combination of both. The usual spatial resolution of GCMs is 100-300 km^2, resulting in a rather coarse than detailed grid size. When assessing the impact of climate change on human health, it is important to use a detailed climate data, with accurate estimations of short-term variations and extreme conditions of the climate. Therefore it is better to use regional climate models (RCMs), which provide a detailed and local future climate projection, with a spatial resolution of down to 2.5 km^2 (Nik, 2012).

In this study, sets of representative weather data sets based on RCM data are used, including typical downscaled year (TDY), representing the typical conditions; extreme cold year (ECY), representing the coldest conditions; and extreme warm year (EWY), representing the warmest conditions (Nik, 2016). Three time periods are considered: 2010-2039 (P1); 2040-2069 (P2); 2070-2099 (P3). The data was developed using 13 RCMs, which are based on future climate scenarios developed by the Rossby Centre and represent three Representative Concentration Pathways (RCPs): 2.6, 4.5 and 8.5. The representative weather data sets (TDY, ECY and EWY) were developed in a way to represent the most typical, coldest, and warmest months of the 30-year periods considering 13 future climate scenarios. For more details about the method and synthesizing weather data sets, the reader is referred to Nik (2016). By using the synthesized weather sets the computational time is considerably reduced without compromising without compromising the accuracy of the results.

The three weather scenarios for all three time-periods are illustrated in figure 8 for Malmö, figure 9 for Stockholm and figure 10 for Umeå. The TDY is represented in black, EWY in red and ECY in blue. As illustrated, TDY lays in between ECY and EWY and represents the typical weather, while EWY is concentrated on the top of the temperature distribution and ECY on the lower end representing both extremes. It is important to consider that the EWY and ECY weather data sets represent the pessimistic scenarios over one year with very low probability in a real world, however the monthly values (e.g. having a very warm July) have the same probability as any other scenario (e.g. no less probability than any other July in the considered data set) (for more details, check Nik 2016).

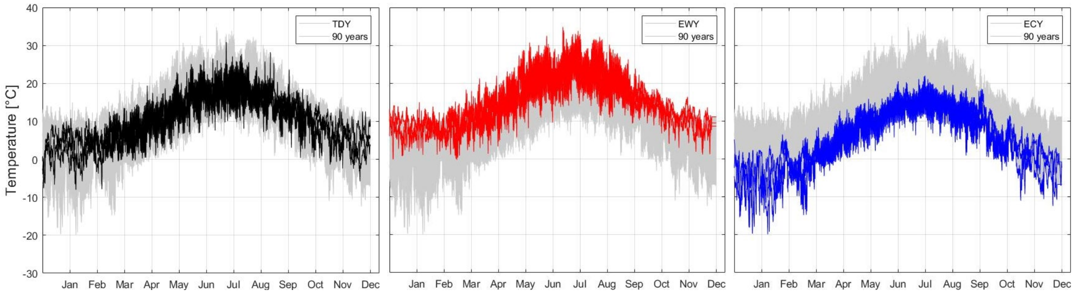

Figure 7:Temperature course in TDY, EWY, ECY between 2010 and 2099 of Malmö. TDY - black, EWY - red, ECY - blue, combined over 90 years – grey

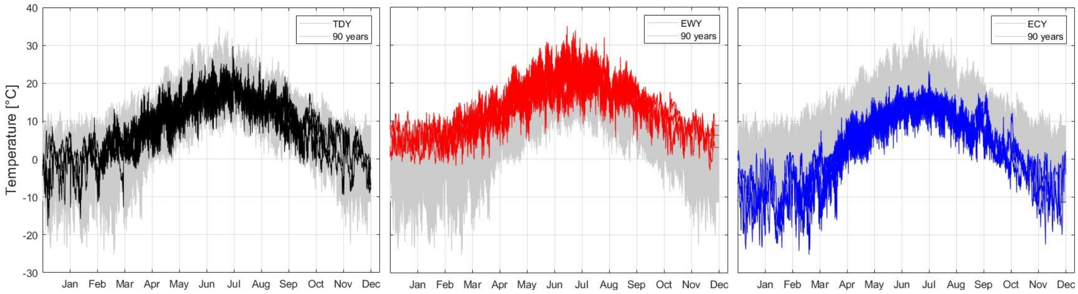

Figure 8:Temperature course in TDY, EWY, ECY between 2010 and 2099 of Stockholm. TDY - black, EWY - red, ECY - blue, combined over 90 years – grey

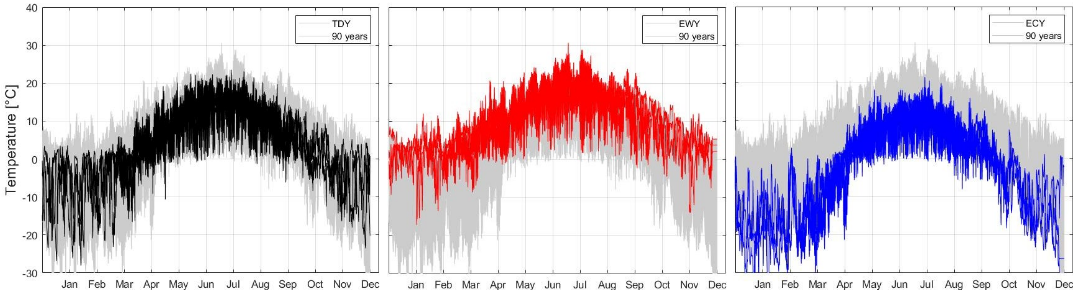

Figure 9: Temperature course in TDY, EWY, ECY between 2010 and 2099 of Umeå. TDY - black, EWY - red, ECY - blue, combined over 90 years – grey

Mean temperatures in TDY for Malmö vary between 9.2°C and 10.6°C, in EWY between 13.3°C and 15.6°C and in ECY between 4.3°C and 5.6°C for P1, P2 and P3. Coldest months are January/ February, reaching a minimum temperature of -19.85°C in ECY-P1. Warmest month for all periods is July, reaching a maximum temperature of 34.84°C in EWY-P3. Mean temperatures in Stockholm vary between 6.7°C and 8.3°C, 10.8°C and 13.7°C and 0.6°C and 2.0°C for TDY, EWY and ECY respectively. Similar as in Malmö, coldest months are January/ February, reaching a temperature of -25.13°C in ECY-P1. Highest temperatures are reached in July, with a maximum of 34.97°C in EWY-P3. Yearly mean temperatures in Umeå vary between 1.7°C and 3-7°C in TDY, 2.4°C and 10.5°C in EWY and -4.7°C and -4.0°C in ECY. The highest and lowest temperature of the weather data occur, as in Malmö and Stockholm, in ECY-P1 and EWY-P3 with -40.12°C and 30.65°C. Mean monthly temperatures for all weather files and cities are presented in appendix 8.4

3.5 Health impact assessment

The impacts of climate change and mitigation measures within the building sector on the indoor environment and human health are evaluated by assessing the thermal discomfort and risk of higher vulnerability in terms of morbidity and mortality. Three different methods calculating the human exposure to extreme temperatures are being assessed and compared to each other by calculating the excess mortality and hospitalization due to future climatic conditions.

3.5.1 Population at risk

In this study, the Swedish population is divided into two age-groups: people 0-64 years and people 65+ years. Sweden's society is aging, with over 20% being older than 65 years (Statista, 2021). Previous research has shown, that older people have a higher thermal vulnerability compared to younger people due to a dysfunctional thermoregulation system (Ormandy and Ezratty, 2016). Further, the elderly people are more susceptible to suffer from health impacts due extreme temperatures indoors due to climate change, because they are more likely to spend more time indoors than younger adults. Table 9 presents the number of deaths and hospitalizations per day (per 100 000 inhabitants) due to cardiovascular and respiratory diseases. Values for hospitalization numbers were obtained from a study by Fonseca-Rodríguez et al. (2021), while the values for mortality were retrieved from the Statistical Database for Cause of Death from the Swedish National Board of Health and Welfare (Socialstyrelsen, 2021). Data was retrieved using the international disease classification codes for cardiovascular and respiratory diseases, ICD-10:I00-I99 and ICD-10:J00-J99 respectively. The values in table 9 represent the average numbers per 100 000 people per day for the period of 1997 – 2014 for deaths and 1992 – 2014 for hospitalizations.

Table 9: Number of deaths and hospitalizations /100,000/day, for cardiovascular and respiratory diseases, ages 0-65 and 65+

		Skåne		**Stockholm**		**Umeå**	
		0-64	65 +	0-64	65 +	0-64	65 +
Summer	Mortality	1.62	131.29	1.62	112.02	1.59	129.57
	Hospitalization - cardiovascular disease	14.72	40.80	51.06	139.57	3.68	10.51
	Hospitalization - respiratory disease	9.49	12.11	32.34	40.90	2.31	2.56
Winter	Mortality	2.24	181.31	2.24	154.69	2.20	178.93
	Hospitalization - cardiovascular disease	16.54	44.86	56.90	151.82	4.22	11.72
	Hospitalization - respiratory disease	14.99	16.10	50.59	53.04	3.64	3.59

3.5.2 Measurements

The climate change impact assessment on indoor environment and human vulnerability is carried for two periods, mainly summer and winter. The month July was chosen to represent the summer period (31 days) and the month February to represent the winter period (28 days). These months represent the warmest and coldest month on average over a whole year in Sweden.

3.5.3 Risk of increase thermal discomfort

The risk of increase thermal discomfort is assessed by assessing the number of hours over 26°C and by using the PMV method, to be able to differentiate between the two age groups. The long-term assessment of the thermal comfort conditions and thus the increase of thermal discomfort over time was evaluated using Method A of the European standard ISO 7730, where the number of hours, in which the PMV is outside of a specific range was calculated. The hours in which both human groups feel too warm or too cold, PMV +3 and -3 respectively, was used. The time exposure of the different cases will be used as a base for the comparison.

The indoor thermal comfort was assessed using the indoor climate model in IDA ICE by EQUA, which calculates the thermal comfort based on equations from the European standard ISO 7730 using the PMV method, which takes the temperature, radiation, moisture and draught, occupant clothing and level of activity into account (EQUA, 2022). The standard predicts the overall thermal sensation and degree of discomfort of people by calculating the PMV and PPV, see chapter 2.3. for details of the model (SIS, 2006). To account for all thermal dynamics within the building body, a multi-zone model was created to achieve more realistic results of thermal comfort (Simson et al., 2015). The layout of a typical MFH apartment from the Million Building Program was retrieved from a publication by Stenberg (2013) to create a multi-zone model in IDA ICE. Figure 6 represents the multi-zone model of the representative apartment, including a living room, bedroom, kitchen, and bathroom. The representative room for the study was chosen to be the living room on the top floor oriented to the south, highlighted in red.

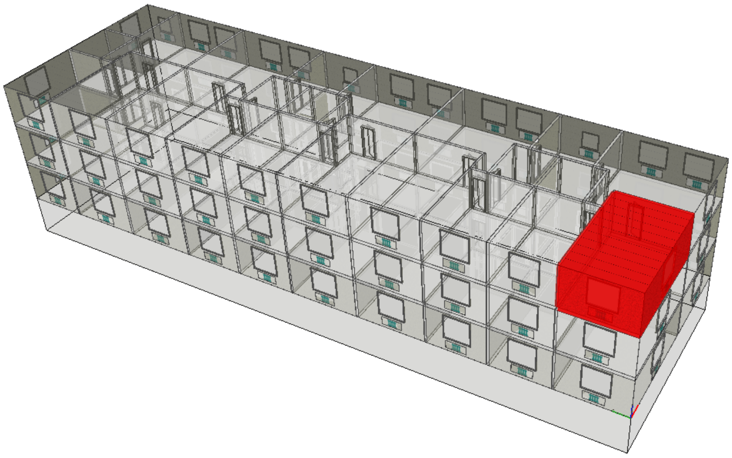

Figure 10: IDA ICE multi-zone simulation model; zone of interest in red

The thermal comfort is assessed separately for winter and summer periods, using climate files for the months of February and July. Table 10 represents the parameters such as activity level, clothing insulation, air velocity and temperatures used for each configuration, with different values depending the season and on the age of occupant.

Table 10: Input parameters for thermal comfort simulations during winter and summer period in IDA ICE

	Summer		**Winter**	
	< 65	65+	< 65	65+
Climate file	July - EWY		February - ECY	
Indoor temperature (min/max)	21/26°C	22/26°C	21/24°C	22/24°C
Metabolic rate (MET)	1.20	1.07	1.20	1.07
Clothing (clo)	0.70	0.90	1.00	1.20
Air Velocity	0.25 l/s		0.15 l/s	
Occupancy	always		always	

The indoor comfort temperature thresholds are based on recommendations from the Public Health Agency of Sweden (SVEBY 1.0, 2012). The operative temperature is measured at a position of an occupant, which is in the middle of the room and 0.6m above the floor, representing a sitting occupant, which is the default setting in IDA ICE (EQUA, 2022). The metabolic rate (MET) of a sedentary (normal) activity in a residential building is 1.20 and the thermal insulation of clothing (clo) is 0.70 according to the standard. These values are based on a study conducted with young adults while elderly people have often a lower average activity. Yi et al. (2022) conducted a study analyzing three different thermal comfort modelling methods for older people of which the PMV method was one. His results showed that PMV is applicable for people of high age, by adjusting the MET to 1.07. A lower MET value leads to a higher thermal insulation of clothing. Therefore it is assumed that the elderly people wear more clothes. The clothing insulation was chosen to 0.9 clo for older people, which is equivalent of one more layer than a regular clothing according to the standard. The clothing insulation was separated into winter and summer clothing, to receive higher accuracy for the results. Clothing insulation values are based on the standard SS EN ISO 7730. The air velocity can influence the general thermal comfort of the human body due to convective heat exchange of the person and the surrounding environment (SIS, 2006). Therefore thresholds for the air velocity were chosen, which are based on BBR. The air velocity in occupied zones should not exceed 0.15 m/s in the heating season and 0.25 m/s during the rest of the year (Boverket, 2020). To simulate more realistic values, natural ventilation was assigned. It was assumed that if the indoor temperature is above 26°C natural ventilation was used by just opening the windows.

Internal gains influence the temperature of a building and can impact the thermal comfort of the occupant. Internal gains through equipment and occupants were accounted for in the simulations. The internal gains were designed with the help of BEN 2 – BFS 2017:6, which is a part of the Swedish building regulation (BEN 2, 2017). According to the standard, the number of people in a two-bedroom apartment is 1.63. For simplifications, the total household energy consumption was set to a template value of 30 kWh/m^2 according to the standard. For the summer season internal gains were set to 100%, while the equipment gains were turned off during the winter season, to assess the worst-case scenario.

For simplifications, surrounding buildings and vegetation, that might shade the building, were neglected in this study. Therefore, results are to be evaluated with cautious because shading affects the temperatures and thus the overheating potential of a building. Integrated shading in the building was not modelled, because it depends on individual behavior and influences the thermal comfort.

3.5.4 Risk of increased vulnerability in form of morbidity and mortality

The assessment of future morbidity and mortality of humans in terms of excess hospitalizations and deaths is based on the application of region-specific temperature functions. The results of region-specific temperature functions is a so called relative risk (RR), which is a measure that represents the change in a chosen risk at any given temperature compared to a reference temperature, which corresponds to the minimum risk of the specific case or the temperature where the risk is the lowest (Vicedo-Cabrera et al., 2021). Rocklöv et al. (2014) established RR of mortality and hospitalizations (for different causes) for the Stockholm region with a case-crossover model using a time-stratified design for a study period from 1990 to 2002. In the time-stratified design the environmental conditions of a specific day, average over one day, were compared to occurring deaths/

hospitalizations of the same day in the same month in the same year to investigate trends and seasonal cycles in mortality, further details of the model can be read in the study by Rocklöv et al. (2014). Input data were daily mortality and hospitalizations numbers for all residents in Stockholm County from the Swedish National Cause of Death Register. The causes of death and hospitalization were classified based on the International Statistical Classification of Diseases and Related Health Problems (ICD-9 for the period 1990-1996 and ICD-10 for the period 1997 and onward). Hospitalizations due to cardiovascular disease (ICD-9: 390–459; ICD-10: I) and respiratory disease (ICD-9: 460–519; ICD-10: J) are the only relevant causes for this study, because these health outcomes are of higher risk due to climate change (WHO, 2018). Table 11 represents the RR values of different age groups for 1°C temperature increase during the summer period and decrease during the winter period and are presented with corresponding 95% confidence intervals. The temperature threshold for the summer period was set to 20.7°C by Rocklöv et al. (2014). For the winter period, the temperature of -4.8°C was chosen, which was the minimum temperature threshold used for assessing cold wave effects by Rocklöv et al. (2014). The RR for winter were assessed over a number of days using temperatures over multiple days. Since the access to daily data was not granted for this study, the -4.8°C were chosen as a threshold for simplifications. The RR in summer was calculated for the period between June – August and the RR in winter for December – February.

Table 11: RR values for summer and winter mortality and hospitalization in Stockholm per 1 ℃ temperature increase in the summer period and 1 ℃ temperature decrease in the winter period

		Summer	**Winter**
	Group	RR (95% CI)	RR (95% CI)
Mortality	All population	1.008 (1.001, 1.015)	1.007 (1.002, 1.011)
	Ages 0-44	1.006 (0.996, 1.015)	1.017 (0.990, 1.046)
	Ages 45-64	1.005 (0.997, 1.013)	1.010 (0.996, 1.023)
	Ages 65-79	1.007 (0.999, 1.014)	1.006 (0.998, 1.014)
	Ages 80+	1.010 (1.002, 1.017)	1.005 (0.999, 1.011)
Hospitalization	cardiovascular disease age < 65	1.000 (0.994, 1.014)	1.009 (0.978, 1.040)
	cardiovascular disease age ≥ 65	1.006 (0.998, 1.014)	1.003 (0.991, 1.014)
	respiratory disease age < 65	1.002 (0.986, 1.017)	1.016 (0.958, 1.077)
	respiratory disease age ≥ 65	1.009 (1.000, 1.018)	1.008 (0.986, 1.029)

This study analyzed the effects of temperature exposure and human health based on temperature intensity rather than heat and cold wave duration. Therefore, only the RR for one unit increase of maximum temperature rather than RR associated with heat wave are presented in table 11, which are based on the study from Rocklöv et al. (2014).Warm and cold temperatures have a different impact on the human health depending on their duration and intensity and different human groups are susceptible to different types of exposure. The choice of neglecting the effect of temperature duration was purposeful, because the model used to calculate the excess vulnerability of people exposed to indoor temperature is based on single temperature exposure rather than duration. To be able to compare the different models, the effect of heat and cold waves on human health is neglected here, even though it is known that different human health impacts are to be expected (Rocklöv et al., 2014). Heat and cold waves are defined when at least for three consecutive days the daily maximum/ minimum temperature is above/below a certain threshold (Lavaysse et al., 2018). In the study conducted by Åström et al. (2020), the heat wave was defined according to the Swedish heat warning system. A heat wave occurs, when the daily maximum temperature is over 26°C for three consecutive days.

To evaluate the impact of climate change on the human health, the daily excess mortality and morbidity for group i were calculated according to equation 2, which was adapted from a study conducted by Taylor et al. (2018):

$$excess\ vulnerability_{d,i} = (T(method)_d - T_{threshold}) * (RR_i - 1) * M_i \qquad (2)$$

Where $T_{threshold}$ is the region-specific heat and cold temperature threshold, RR_i is the relative risk of group i for a 1°C increase/ decrease in temperature above/below $T_{threshold}$ and M_i is the age specific background hospitalization/ death rate presented in table 9. $T(method)_d$ describes a specific- temperature, to assess the impact of climate change on human health. Different temperature parameters are being used in temperature related mortality calculations. In this study three different methods are being compared to each other, which are described below. Two of the methods evaluate the excess risk due to changing outdoor temperatures, while the third one takes the indoor temperatures into account. Comparing two commonly used methods with outdoor temperatures and one new method taking indoor temperatures into account will show, if the outdoor temperatures are a good enough estimation for people exposed to indoor temperatures, due to the relation of outdoor and indoor temperatures. Projections of excess mortality and morbidity were calculated for building A, B and C for each location. Calculations were repeated for a representative month for EWY and ECY. Demographic and housing stock changes are being neglected in this study, which is why results represent projections rather than predictions of future human vulnerability. Further, it is assumed that the RR and M stays constant over the next 100 years.

3.5.4.1 Method A

Method A projects future temperature-related vulnerability of humans based on mean outdoor temperature changes. The mean outdoor temperature is a commonly used climate parameter to project the impact of future climate and temperature related vulnerability and used in studies conducted by Doyon et al. (2008), Doherty et al. (2009), and Knowlton et al. (2007). A main reason for the use of mean temperature is due to its common availability in climate models (Huang et al., 2011). To project the future human vulnerability due to climate, the excess morbidity and mortality will be calculated using the changes in mean outdoor temperature according to equation 3.

$$excess\ vulnerability_{d,i} = (T(mean)_d - T_{threshold}) * (RR_i - 1) * \ M_i \tag{3}$$

Where $T(mean)_d$ is the mean daily outdoor temperature for the analyzed future weather dataset. Results will imply how the future mean outdoor temperature will affect the risk of hospitalization.

3.5.4.2 Method B

Method B projects future temperature-related vulnerability of humans like method A, with the difference of using maximum daily outdoor temperature instead of mean outdoor temperature. Maximum temperature is another widely used weather measure to assess heat-related mortality and was applied in studies conducted by Gosling et al. (2009), Dessai (2003) and Takahashi et al. (2007). The excess vulnerability was calculated according to equation 4:

$$excess\ vulnerability_{d,i} = (T(max)_d - T_{threshold}) * (RR_i - 1) * \ M_i \tag{4}$$

Where $T(max)_d$ is the max daily outdoor temperature for the analyzed future weather dataset.

3.5.4.3 Method C

Method C projects future temperature-related vulnerability based on indoor temperature exposure and is adapted from a study conducted by Taylor et al. (2018; 2021). This method consideres the possible effect of the building characterisitcs on the indoor environment and human exposure by assessing the health impacts for different human groups due to exposure to the indoor environment and is therefore the first known model combining building physics and health. The method consists of three steps: building simulation tool to generate indoor temperatures based on different outdoor temepratures (1), estimation of temperature anomalies between indoor and outdoor temperatures of each building construction (2) and the calculation of excess vulnerability (3).

Simulating indoor temepratures:

The hourly indoor temperatures over the one month (July and February in this work) were generated using the simulation tool IDA ICE and input paramaters as described in chapter 3.5.2. This hourly data was processed using MATLAB, to the average $T_{in,d}$ of the simulated two-day rolling mean maximum indoor temperature ($T_{max,in}$) within incremental ranges of two-day rolling mean maximum outdoor temperatures ($T_{max,out}$). The moving average over two days was calculated to reduce the extreme fluctuations of temperatures and create a smoother temperature distribution, to account for modelling uncertainties, which could create false extreme indoor temperatures.

Calculating temperature anomalies:

Temperature anomalies were calculated using the temperature exposure for an individual inside a building and the average of the city and building. The daily temperature anomalies were calculated for each building and location for cold and warm weather using equation 6, representing the building's positive or negative indoor anomaly relative to the indoor temperature threshold. The heat/cold anomaly $\Delta T(heat/cold)_{i,k}$ for individual i on day d was calculated according to equation 6, where $T_{in,d}$ is the building specific temperature on a given day. $T^{*}{}_{in,d}$ is the occupant-weighted temperature threshold of 26°C for heat calculation and 21/22°C for cold calculation.

$$\Delta T(heat/cold)_{i,d} = T_{in,d} - T^{*}{}_{in,d} \tag{6}$$

Excess vulnerability calculation:

Projections of heat- and cold-related vulnerability calculations were carried out under the assumption that the temperature-vulnerability relationship is the same for indoor temperatures as for outdoor temperatures. For heat and cold, the heat and cold anomaly was added to the outdoor temperature of the same day, to give the effective temperature exposure for an individual:

$$T(mean, effective)_{i,d} = T(mean, out)_{d} + \Delta T(heat/cold)_{i,d} \tag{7}$$

The excess vulnerability was than calculated according to following equation:

$$excess\ vulnerability\ _{p} = \left(T(mean, effective)_{i,k} - T_{heat/cold}\right) x\ (RR_{i} - 1)\ x\ M_{i}) \tag{8}$$

4 Results and Discussion

In the following chapter, the results of this study are being presented and discussed. Results are presented desperate for each city and method. By means of building A, B or C it is mainly referred to the construction types as described in chapter 3.4; original state (building A), retrofit design (building B) and new design (building C). When referring to future climate conditions, P1 refers to the year 2010-2039, P2 to 2040-2069 and P3 to 2070-2099.

4.1 Model Verification

The building model created in IDA ICE was verified using reference values for heating demand from the TABULA webtool and the Swedish building regulation BBR 29 using the TMY weather data from the IDA ICE weather data base. Figure 11 represents the results, the blue square represents the reference heating demand, and the orange diamond the simulated heating demand in IDA ICE. The letters A, B and C stand for the different building construction types: original (A), retrofit (B) and newly built (C). For building A and B in all cities, the difference varies between 2% and 9%. Building A and B located in Malmö resulted in the lowest discrepancies compared to the reference value, with 2.0% for building A, 3.3% for building B and 7.6% for building C. For Stockholm, same buildings resulted in higher differences with 6.6% (building A) and 8.3% (building B). The higher discrepancies can be traced back to the fact, that Malmö and Stockholm are classified into the same climate zone (III) within the TABULA webtool. Since the climate is slightly colder in Stockholm than Malmö, with yearly mean temperatures of 7.3°C and 8.2°C respectively, the discrepancies are plausible. For building C the simulated heating demand is 23% (Malmö), 36% (Stockholm) and 33% (Umeå) lower than the reference value. Building C consists of a new construction, which was designed according to values set by BBR 29. The reference values act here as thresholds which are not to be exceeded. The building model resulted in an overall thermal transmission of the envelope of 0.30 W/(m^2K), which is 0.10 W/(m^2K) lower than the threshold and thus results in lower heating demand.

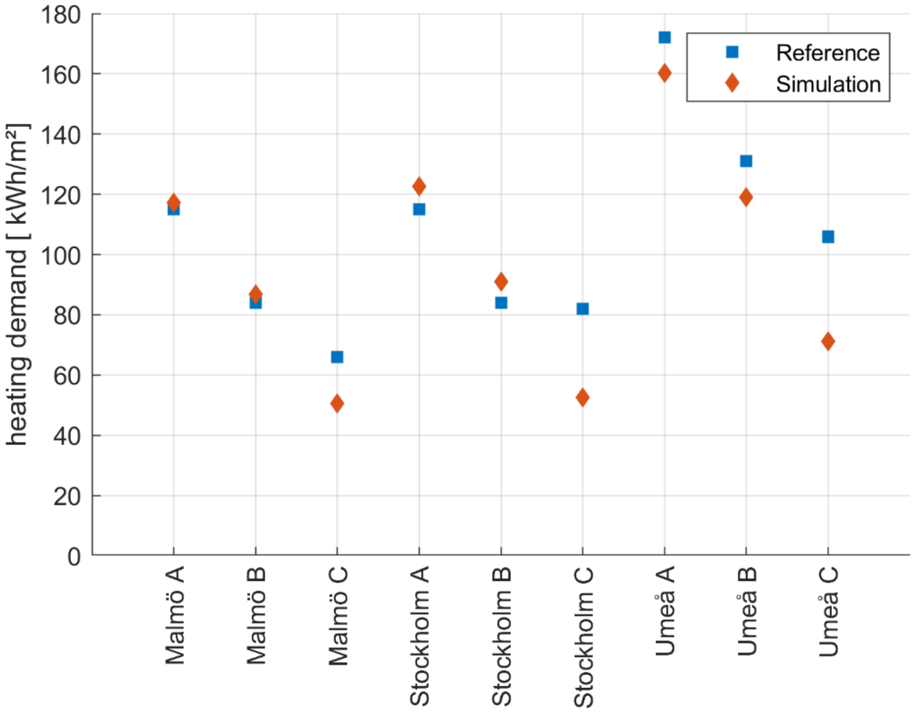

Figure 11: Heating demand for the three analyzed building located in Malmö, Stockholm and Umeå; orange - simulated heating demand, blue - reference heating demand

4.2 Future climate

The hourly outdoor temperature distribution for the typical dataset TDY and the two extreme future climate weather data sets EWY and ECY are shown for the three analyzed cities Malmö, Stockholm and Umeå using a boxplot in figure 12 and 13. The boxplot for each summer period, the month of July, represents 290 160 temperature datapoints, combining 13 GCM's and the three RCP's for 744 hours (July) for each 30-year period. The boxplot for each winter period, month of February, represents 262 080 temperature datapoints, representing 672 hours of each February for the 30-year periods combined for 13 GCM's.

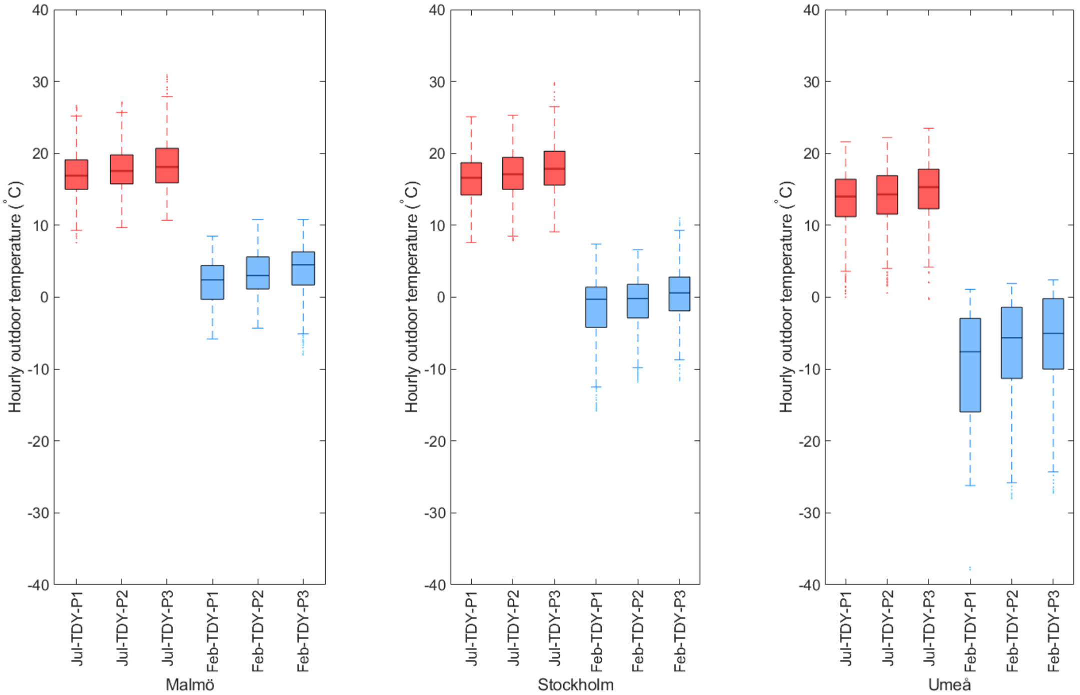

Figure 12: Hourly outdoor temperature distribution of the typical weather dataset TDY for three periods: P1(2010-2039), P2(2040-2069), P3(2070-2099); summer period (July) – red, winter period (February) - blue

The representative typical conditions in figure 12 for the next 100 years, indicate an increase of average temperatures in the month of July in all three cities, with average temperatures between 17.0 and 18.4°C in Malmö, 16.5 and 18.0°C in Stockholm and 13.4 and 14.9°C in Umeå. Projections show, that typical conditions can reach temperatures up to 30.9°C in Malmö, 29.8 in Stockholm and 23.5°C in Umeå. Projections of the outdoor temperatures for the month of February show an increase in average temperatures, with less frequent extreme cold events. Average temperatures increase from 2.1 to 3.9°C in Malmö, -1.8 to 0.2°C in Stockholm and -9.5 to -6.2 in Umeå. Table 12 represents the average, minimum and maximum outdoor temperature for the three cities and the representative months of July and February for projections of the TDY weather dataset.

Table 12: Average, minimum and maximum outdoor temperatures of January in TDY (2010-2099) for the three locations: Malmö, Stockholm, Umeå

		Malmö			**Stockholm**			**Umeå**		
		T_{mean} (°C)	T_{min} (°C)	T_{max} (°C)	T_{mean} (°C)	T_{min} (°C)	T_{max} (°C)	T_{mean} (°C)	T_{min} (°C)	T_{max} (°C)
January	TDY-P1	2.1	-5.8	8.5	-0.9	-11.3	6.6	-9.5	-37.9	1.1
	TDY-P2	3.1	-4.3	10.8	0.2	-11.6	11.0	-6.9	-28.0	1.9
	TDY-P3	3.9	-8.0	10.8	13.4	0.0	21.6	-6.2	-27.2	2.4
July	TDY-P1	17.0	7.6	26.6	16.5	7.6	25.1	13.4	0.0	21.6
	TDY-P2	17.8	9.7	27.1	17.2	7.9	25.3	13.9	0.6	22.2
	TDY-P3	18.4	10.7	30.9	18.0	9.1	29.8	14.9	-0.3	23.5

Considering the most extreme conditions for the next 100 years in figure 13, the outdoor temperatures of the month July will increase in all three cities, with average temperatures between 21.4-23.5°C for Malmö, 19.8-22.7°C for Stockholm and 16.0-19.6°C for Umeå. The probability of temperatures being above 30°C will increase especially in the south of Sweden, where outdoor temperatures can reach up to 35°C. Even in the north, it is probably that temperature can rise to 30°C in P3. The effects of global warming can be also seen in the coldest month February, where the monthly representative coldest conditions over the next 100 years increase from -3.5 to -1.8°C in Malmö, -10.4 to -9.°C in Stockholm and -20.0 to -18.1 °C in Umeå. While the range of temperatures during the warm period increases slightly, with more extreme temperatures in summer, it is most likely that the temperature range for the cold period will decrease, with less extreme cold temperatures in the future, as the blue boxplots represent.

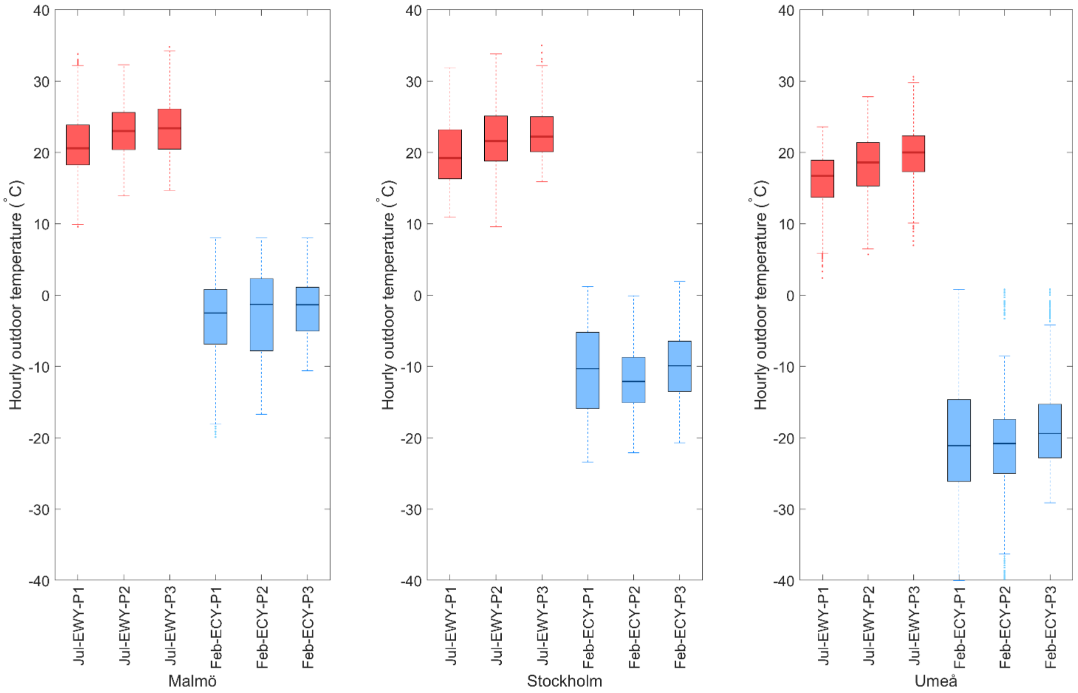

Figure 13: Hourly outdoor temperature distribution of the extreme weather dataset ECY and EWY for three periods: P1(2010-2039), P2(2040-2069), P3(2070-2099); summer period (July) – red, winter period (February) - blue

Table 13 shows the average, minimum and maximum outdoor temperature for the three cities and the representative months of July and February under the extreme future climate projections

Table 13: Average, minimum and maximum outdoor temperatures of January in ECY (2010-2099) and July in EWY (2010-2099) for the three locations: Malmö, Stockholm, Umeå

		Malmö			**Stockholm**			**Umeå**		
		mean	min	max	mean	min	max	mean	min	max
January	ECY-P1	-3.5	-19.9	22.0	-10.4	-25.1	19.8	-20.0	-40.1	18.5
	ECY-P2	-2.6	-18.1	20.5	-11.5	-23.3	18.9	-20.7	-31.4	21.5
	ECY-P3	-1.8	-14.3	20.3	-9.9	-20.1	23.2	-18.1	-30.7	20.5
July	EWY-P1	21.4	1.1	33.8	19.8	-1.4	31.9	16.0	-14.1	23.9
	EWY-P2	23.1	-0.2	32.3	21.9	-2.9	33.8	18.2	-17.2	27.8
	EWY-P3	23.5	1.9	34.8	22.7	-0.7	35.0	19.6	-6.3	30.7

4.3 Future energy demand

The annual average heating demand for the analysed buildings in the three cities is represented in table 14. The results were estimated using the future weather data for TDY, EWY and ECY and the IDA ICE energy model. The results indicate that the yearly heating demand per m^2 will decrease over the next 100 years, for all analysed weather scenarios. For buildings located in Malmö, the south of Sweden, the projected yearly heating demand shows a decrease of heating demand over the periods on average between 5-7% for all constructions. Considering the extreme climate files, same trend can be observed. For the same buildings located in Stockholm, a decrease of energy demand from P1 to P2 of about 6% can be observed, with a slightly higher decrease between P2 and P3, of 10% for TDY. For the projections of the extreme weather files, a decrease in heating demand of 12-14% can be seen under EWY dataset, and between 1-7% for ECY dataset, with lower increase from P1 to P2 compared to P2 and P3. TDY projections for the buildings located in Umeå show a similar heating energy reduction, of 4-7%. For EWY projections, a reduction of heating demand with up to 37% between P1 and P2 and 14% between P2 and P3 is shown. For ECY projections a slight increase, of less than 1%, between P1 and P2 is shown, while a decrease of 3% between P2 and P3 can be expected.

Table 14: Annual average heating demand in kWh/m^{2}for the three periods, for each construction being located in Malmö, Stockholm and Umeå

Heating energy demand (kWh/m^2/year)		**Period 1**				**Period 2**			**Period 3**		
		Past climate	**TDY**	**EWY**	**ECY**	**TDY**	**EWY**	**ECY**	**TDY**	**EWY**	**ECY**
Malmö	A	117.3	77.8	51.9	121.7	73.4	48.3	108.9	68.1	44.4	102.8
	B	86.8	58.1	38.7	90.9	54.9	35.9	81.3	50.8	33.1	76.8
	C	50.6	29.1	19.6	42.4	26.7	18.5	37.4	24.9	17.6	34.4
Stockholm	A	122.6	108.3	76.5	162.1	102.1	65.8	160.6	92.3	57.5	149.5
	B	91.0	80.7	56.9	120.9	76.2	49.0	119.8	68.8	42.8	111.6
	C	52.5	41.9	30.6	62.1	40.1	27.1	62.4	36.4	23.8	57.8
Umeå	A	160.3	167.5	167.8	230.8	155.1	109.7	231.2	147.7	94.1	223.4
	B	119.0	123.4	124.4	171.9	114.3	81.6	172.1	109.4	69.9	166.5
	C	71.3	70.6	76.7	97.1	65.3	48.2	98.8	62.7	41.3	94.5

Results indicate in general, that annual average heating demand will decrease between 5-10% under the TDY projections for all cities. Comparing the energy demand of different construction types to each other, results show, that the average yearly heating demand can be reduced with up to 25% with retrofit measures and up to 62% with the new, energy efficient construction.

Even though these results indicate an overall decrease in energy demand it is important to mention, that the estimated cooling demand was neglected here ad could increase the total yearly energy demand. In a study Yang et al. (2021) an overall decrease in heating energy demand could be observed by using the same climate files. Yang et al. (2021) analysed further the possible cooling demand as a result of climate change, and found that in colder climates like Sweden the average cooling demands during the summer period (June, July, August) will increase between 25-40% between P1 and P2 and to 23 and 36% between P2 and P3.

4.4 Thermal comfort assessment

The thermal comfort assessment was conducted using the typical and extreme weather files. The results under projections of TDY will be presented in the beginning of the chapter, mainly due to the fact that the projections indicated a low impact on thermal discomfort due to relatively moderate temperatures indoors. The results of thermal comfort assessment using EWY and ECY are presented in detail, to show the worst-case scenario and possible maximum effect of future extreme weather on indoor temperature and on human comfort perception. Even though it is very unlikely that the extreme temperatures will occur consecutive over a month, it is important to analyses the effect of extreme temperature exposure.

4.4.1 Typical climate projections

The indoor air temperature distribution for the typical weather projections are displayed using a boxplot in figure 23, 24 and 25 in appendix 8.5, representative for the three analyzed construction types located in the cities of Malmö, Stockholm and Umeå. Results indicate, that indoor temperatures remain moderate over the next 100 years, with higher temperatures in building C compared to the two other buildings, in all three cities. Projections indicate that indoor temperatures over 30°C only occur in building C located in Malmö in P2 and P3 as located in Stockholm in P3. Table 15 represents the projections of discomfort hours over the summer period, as well as the maximum indoor temperature in each construction under the typical weather projections.

Table 15: Number of overheating hours and $T_{max,indoor}$ for Building A, B and C located in Malmö, Stockholm and Umeå using TDY projections

		TDY1-P1		TDY1-P2		TDY1-P3	
		Hours over 26°C	$T_{max,\ indoor}$ (°C)	Hours over 26°C	$T_{max,\ indoor}$ (°C)	Hours over 26°C	$T_{max,\ indoor}$ (°C)
Malmö	A	174	27.15	203	27.47	228	28.64
	B	15	26.81	32	27.08	30	27.30
	C	53	29.90	95	30.07	119	32.46
Stockholm	A	125	27.02	194	27.02	201	28.68
	B	13	26.71	10	26.30	30	27.03
	C	38	29.04	42	28.00	50	30.87
Umeå	A	34	26.64	70	27.01	109	27.07
	B	0	25.37	0	25.49	0	25.52
	C	0	25.78	0	25.81	5	26.36

In accordance with the Swedish Public health Agency, overheating occurs if the temperature exceeds 26°C indoors. The highest risk of overheating under the TDY projections is in buildings located in Malmö, followed by Stockholm and Umeå. Even though highest temperatures are estimated to occur in building C, the number of overheating hours is the highest in building A. Risk of overheating increases with less than 5% for all buildings located in Malmö over the periods, with 3-4% for building A, 2% for building B and 3-5% for building C. For the same buildings being located in Stockholm, the projection resulted in general lower number of overheating risks, with an increase between 1-5% for building A, 1-3% for building B and 1% for building C. Projections for Umeå indicate an increase of overheating for building A of about 5% for all periods, with no overheating risk for building B and C. Results of the TDY projections on three different construction types located in Malmö, Stockholm and Umeå indicate, that Malmö is more susceptible towards climate change and risk of discomfort exposure for people living in Malmö, while people living in Umeå are of almost no risk under TDY projections. This is mainly due to the fact that climate change will happen to a higher extend in the south compared to the north.

4.4.2 Extreme climate projections: Malmö

The indoor air temperature distribution for the extreme future climate datasets EWY (red) and ECY (blue) is shown for the three assessed building construction types located in Malmö using a boxplot in figure 14. Considering the EWY and ECY and the possible warmest and coldest climate projections for the future, building A and C showed a higher temperature range over the considered months (July and February) compared to building B. Building B will maintain more constant temperatures, resulting in the fact that the retrofit design is more resilient towards extremes of the future climate. In addition to that, building

B has the highest thermal mass, reducing the indoor temperature fluctuations higher compared to the other buildings through storing heat and releasing it when the surrounding here cooled down (Sala Lizarraga and Picallo-Perez, 2020).

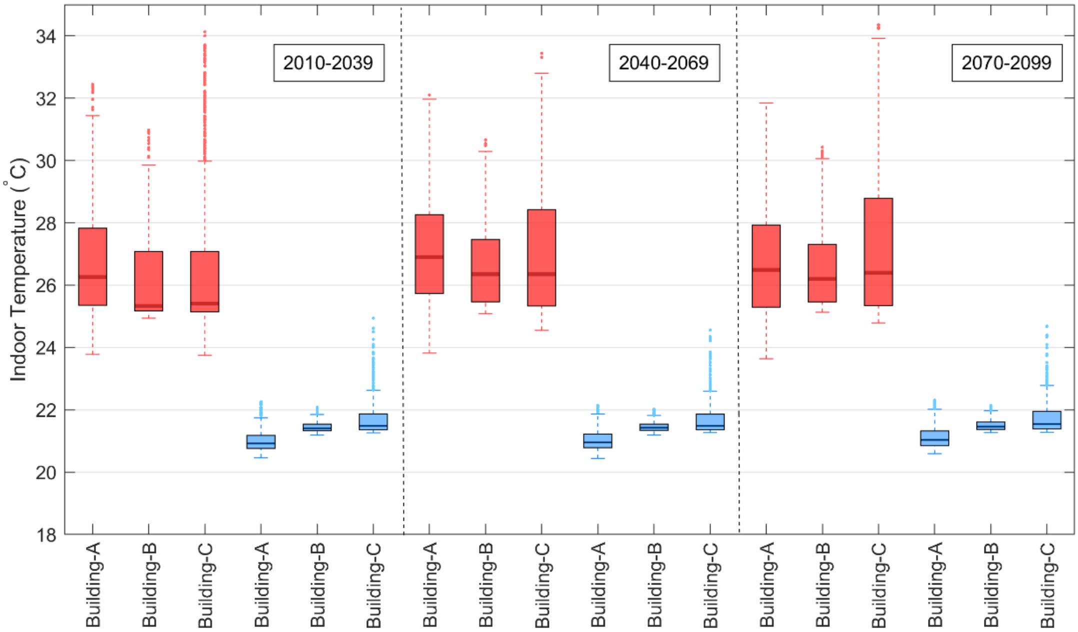

Figure 14: Indoor air temperature distribution for the EWY (red) and ECY (blue) datasets for the three analyzed buildings in Malmö

The temperatures range is between 23.78°C and 34.35°C with an average of 26°C and 27°C in the three periods in building A. The temperature range for building B is not as high as building A, with temperatures between 24.94°C and 30.50°C, indicating that renovation measures of higher insulation thickness and lower infiltration rate create a more constant indoor environment. But in contrast to that, the minimum temperature for the analyzed summer period is about 1°C warmer than for building A, highlighting the fact that an air tighter building envelope in general increases the temperature indoors. Temperatures in building C reach the highest indoor temperatures compared to the other constructions, with maximum temperatures up to 34.50°C, which will increase in frequency with time. Comparing the indoor temperature performance of the three buildings for the winter period, similar results can be seen. Constant temperatures are reached in building B, while building C resulted in the warmest temperatures, with average temperatures of 21.77°C and reaching maximum temperatures of 24.90°C even in winter.

To assess the hours of overheating in summer, a temperature threshold of 26°C was chosen, as set by the Swedish Public Health Agency. Building A resulted in 413 hours of overheating in P1, 522 hours in P2 and 437 hours in P3. Resulting in the fact that people living in building A would experience between 55% and 70% of the time thermal discomfort due to extreme weather. In contrast to that, thermal discomfort occurs for about 35 to 57 % of the time in building B, with 262 hours in P1, 428 hours in P2 and 405 hours in P3. Lowest number of overheating hours were measured in building C with 240 hours in P1 and 412 hours in P2 and P3 corresponding to 32 to 55 % of the summer period. Although the number of overheating hours is the lowest for building C, the average indoor temperature is about 1°C higher compared to building B and extreme air temperatures occur more frequent on building C, as the boxplot in figure 14 represents. Table 16 represents the number of overheating hours occurring in July, as well as their average temperature. The hours account for a 24-hour occupied building, which is an overestimation since adults and young people leave the home to go to work or school. But in contrast to that elderly spent most of their times at home (Ormandy and Ezratty, 2016). According to the Swedish building regulation buildings are designed with a regular occupancy of 14h (Boverket, 2022). Accounting for the lower occupancy, the overheating hours are reduced on average for 44.5% over the next century. Therefore, if the regulations are followed during the design phase, overheating hours could be underestimated drastically. Building A showed under an occupancy of 14 hours a day (08:00-17:00 out of the house), a reduction of overheating hours of 50% in P1, 48% in P2 and 39% in P3. In building B the reduction is between 41%, 44% and 33% for the projected future climate periods. In building C the hours for the 14h occupancy are 50% lower in P1, 53% in P2 and 43% in P3. The percentage is calculated regarding overheating occurring under extreme future climate projections and represent an overestimation. But it can be clearly seen that climate change and the extreme temperatures will have an impact on the indoor environment and differ regarding occupancy. The fact that the number of discomfort hours is reduced 44.5% if 8h of the day are neglected shows, that people who spent most of their times indoor, like the elderly or people with preexisting diseases, are more susceptible to suffer from the effects of climate change. No active or passive measures other than opening the window if the temperature exceeds 26°C were accounting for, highlighting the fact that the results are overestimations. Using for example shading devices will avoid solar gains and therefore significantly reduce the extreme indoor temperatures and improve thermal comfort (Taylor et al., 2018a).

Table 16: Number of overheating hours and their average temperature for Building A, B and C located in Malmö

	Building A		**Building B**		**Building C**	
	Hours above 26°C	T_{mean} (°C)	Hours above 26°C	T_{mean} (°C)	Hours above 26°C	T_{mean} (°C)
EWY-P1	413	28.0	262	28.0	240	29.5
EWY-P2	523	27.9	429	27.4	413	28.5
EWY-P3	395	31.0	366	30.4	385	30.8

Thermal discomfort in winter is not presented, because no thermal discomfort could be detected for the analyzed buildings being in Malmö. This is since the heating demand was designed to maintain a minimum temperature of 21°C indoors. If the heating system is designed accordingly, no problem with thermal discomfort in winter is to be expected.

The indoor thermal comfort perception of a human is not only influenced by the air temperature, but also by the age and clothing insulation (Göransson and Götharson, 2015). To account for these factors, the PMV method was used to assess the thermal comfort of two different age groups: people aged between 0-65 years and people above 65 years. Hours where the PMV-index exceeds 0, can be classified as thermal discomfort. Figure 15 presents only the number of hours outside of PMV-index three for the summer period. Only the results for PMV-index are presented here because they show the effect of temperature intensity. The sum of all hours over PMV-0 resulted in the same trend as seen in table 16 and can be seen in table 24 in appendix 8.6. The negative PMV-index is neglected in the results, since temperatures to not fall below 21°C and thus people will not feel too cold in the summer months.

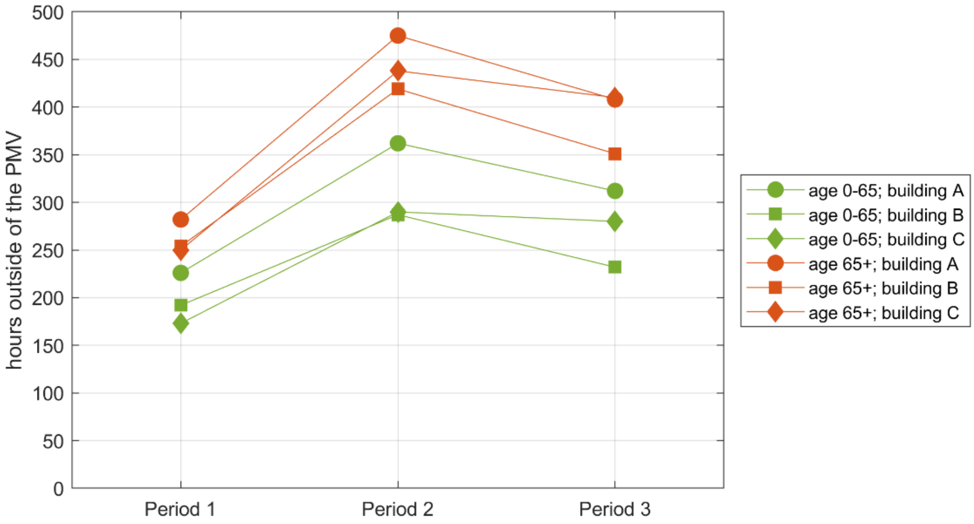

Figure 15: PMV-index 3 for people living in Building A (circle), B (square) and C (diamond) located in Malmö; people aged 0-65 colored in green, people aged 65+ colored in orange

Results presented in figure 15 indicate, that in general people aged 65+ (orange colored) will experience more hours outside of the PMV range than people below 65 years (green colored), with highest number in building A, followed by building C and B. This is mainly due to the reason, that older people have a lower metabolic rate, making them feel colder compared to young adults and thus dress more (Yi et al., 2022). In this study people aged 65+ were simulated with a metabolic rate of 1.07 MET and 0.9 clo, while young adults are simulated with 1.20 MET and 0.7 clo to account for the age differences. The PMV calculation is very sensitive especially to these two parameters, which stand for the results. While elderly experience 282 hours of feeling too hot in P1 in building A, they experience

254 and 250 hours of feeling too hot in building B and C respectively. Comparing this to people below the age of 65, adults experience around 10% less hours outside of the range with 226 hours in building A, 196 in B and 173 in C respectively. Similar trend can be seen in P2, with up to 26% more hours outside of the range. Elderly people experience up to 475 hours in building A, 419 and 438 hours in building B and C, while adults experience 362 hours outside of the comfort range in building A, 287 in building B and 290 hours in building C. The difference in P2 is that people feel more hours outside of the range in building C compared to building B, resulting in the fact that building C is more vulnerable to more frequent extreme outdoor temperatures. P2 showed a higher frequency of extreme outdoor temperatures compared to P1, as shown in figure 12, highlighting the consequence and susceptibility of buildings that have a low infiltration rate and airtight building envelope. As illustrated in figure 15, less hours outside of PMV-range 3 are projected for P3 compared to P2. This is mainly due to the fact, that in several future climate scenarios, extreme warm temperatures reach higher values in P2 than P3 due to assumptions made when creating the projections.

Results indicate, that older people are more susceptible to suffer from the future climate projections and that the thermal perception of humans follows the outdoor temperature distributions, which is mainly due to the fact that the buildings are naturally ventilated. The PMV-index for the winter period February is not being presented, because results indicated 0 numbers of hours of people feeling “too cold”. This is mainly due to the fact, that the simulations were conducted with a functioning heating system. Further, results indicate that a tighter building envelope and lower infiltration rate improve the indoor environment, but if the exchange between indoor and outdoor is too limited (due to too high building envelope air tightness), the temperatures become extreme high indoors, causing high thermal discomfort indoors and resulting in the fact, that the building is not resilient towards future climate.

4.4.3 Extreme climate projections: Stockholm

The indoor air temperature distributions for future climate projections for the period of 2010 – 2099 of EWY (red) and ECY (blue) in Building A, B and C located in Stockholm is shown using a boxplot in figure 16. Future climate projections show that indoor temperature for all buildings located in Stockholm will increase with time due to global warming and that extreme temperatures indoors increase in frequency, occurring more often and higher in building C and A compared to building B. Similar results were found in buildings located in Malmö, highlighting the fact that the retrofit design (building B) is more resilient towards extreme temperature projections compared to the two other buildings. While Building C is too airtight and has a too low thermal transmittance, trapping the heat indoors and therefore causing high indoor temperatures (Fisk, 2015).

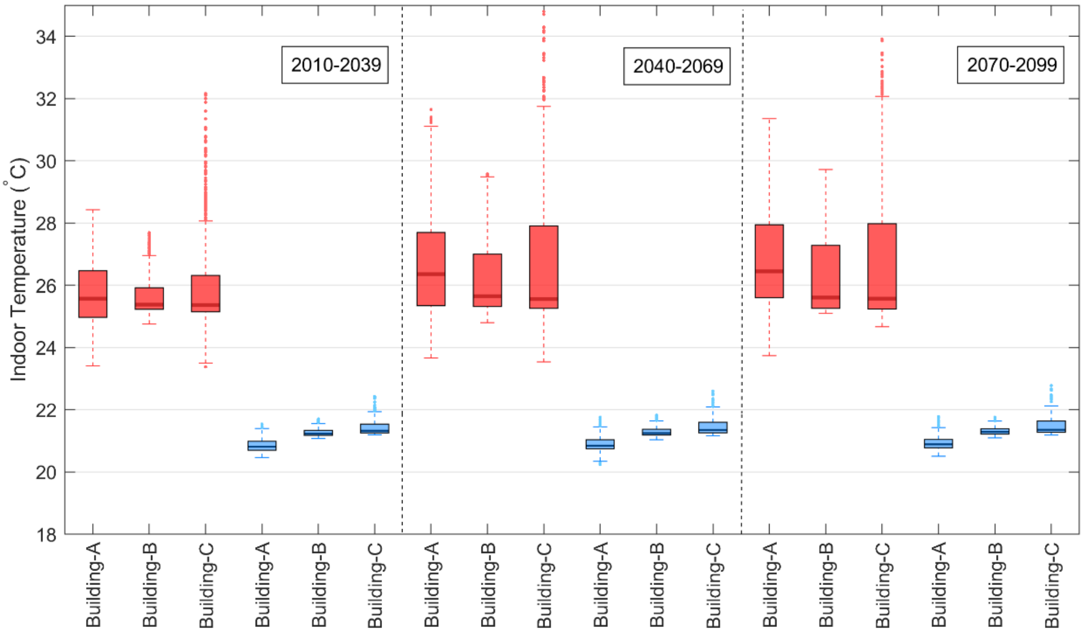

Figure 16:Indoor air temperature distribution for the EWY (red) and ECY (blue) datasets for the three analyzed buildings in Stockholm

Mean temperatures in building A reach under the future climate projections of extreme weather in the summer period on average 25.7°C in P1, 26.6°C in P2 and 26.9°C in P3 with maximum temperatures reaching up to 28.0°C and 31.6°C respectively. Further, temperatures above 30°C indoor become more frequent in the future. Building B located in Stockholm resulted in similar results as being in Malmö, showing the most stable indoor temperatures compared to the two other buildings. Future climate projection indicate that indoor temperatures will increase with time in building B, reaching average indoor temperatures of 25.6°C in P1, 26.2°C in P2 and 26.3°C in P3. Maximum indoor temperatures can reach up to 27.7°C, 29.6°C and 29.7°C respectively to the periods but will in contrast to the two other buildings most likely not reach as high extremes. Indoor temperature conditions of building C are like building A, but with more extreme high temperatures, which is mainly due to the high airtightness of the building envelope. Due to the extreme temperatures in the indoor climate of building C is not as stable as in building B, highlighting the fact, that the indoor temperatures of a building are very sensitive towards airtightness of a building envelope. Projections of the future climate for building C for the month of July will cause average indoor air temperatures of 26.0°C in P1, 26.8°C in P2 and P3. Extreme high temperatures over 30°C will increase in frequency, with temperatures reaching up to 34.8°C. With projections for the winter period (February), building A has compared to the other two buildings the lowest mean temperatures with 20.8°C and 20.9°C for P1, P2 and P3. Mainly caused due to a high infiltration and high thermal transmittance of the building envelope, through which the extreme cold outdoor temperatures get indoors.

Table 17 represents the number of hours over 26°C, representing the number of hours when discomfort occurs according to the Swedish Building regulation. Comparing these numbers to the overheating hours in Malmö, the numbers are in general lower, meaning that buildings located in Malmö are more susceptible to be affected by climate change. Malmö is located further south compared to Stockholm. Under the future climate projections for the summer period, building A will result in up to 278h above 26°C with an average of 26.8°C in P1, up to 435h and 401h in P2 and P3 with an increase in average temperature of the overheating hours to 27.7°C and 31.°C in P2 and P3 respectively. These results highlight the fact, that not only the number of hours over 26 °C become more, but they also increase in temperatures. Same accounts for building B and C, whereas the number of hours over 26°C are lower compared to building A. Future climate projection can cause up to 167h in P1, 318h in P2 and 323h in P3 for the month of July in building B, with average overheating hours between 26.7°C and 27.6°C. Up to 209h, 319h and 30 h in building C in P1, P2 and P3 respectively.

Table 17: Number of overheating hours and their average temperature for Building A, B and C located in Stockholm

	Building A		**Building B**		**Building C**	
	Hours above 26°C	T_{mean} (°C)	Hours above 26°C	T_{mean} (°C)	Hours above 26°C	T_{mean} (°C)
EWY-P1	278	26.8	167	26.7	209	28.0
EWY-P2	435	27.7	318	27.3	319	28.9
EWY-P3	401	31.3	323	27.6	307	29.9

If a lower building occupancy is considered, the risk of thermal discomfort due to future climate projections decreases to a higher grade, compared to Malmö. With the lower occupancy schedule, the number of overheating hours is reduced on average to 56%, with higher extend in building C, followed by A and B. In building C, the number of discomfort hours for the 14-h schedule can be up to 65% lower in P1, 63% in P2 and 58% in P3. Discomfort in building A can be up to 60% lower in P1, 55% in P2 and up to 43% in P3. In building B the risk of thermal discomfort can decrease up to 59%, 54% and 47% for the projected future climate periods.

To account for different age groups of people, the thermal comfort was assessed for the two age groups using the PMV-method as done for Malmö. Figure 17 shows the number of hours which are outside of the PMV-index 3 during the summer period for the three analyzed buildings located in Stockholm. Same as in Malmö, the negative PMV-index is neglected in the results, because they resulted in PMV-Index 0.

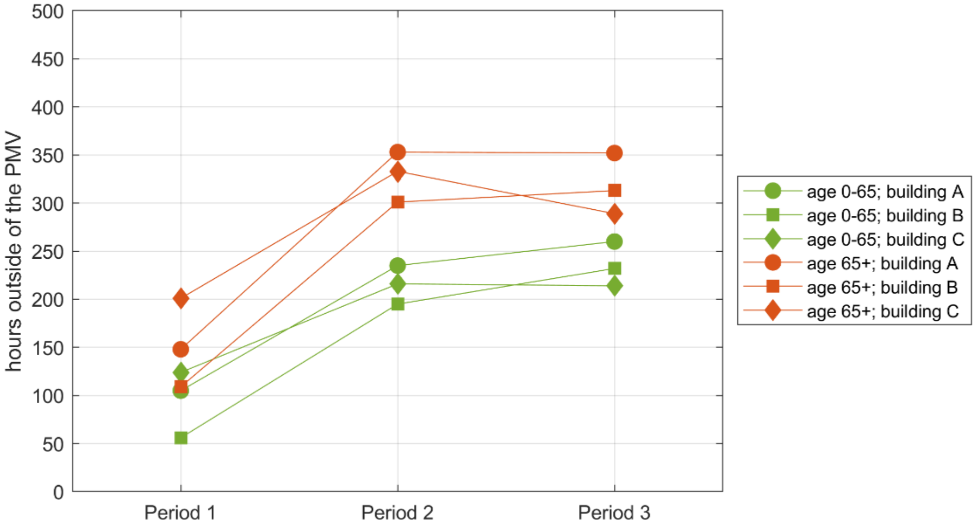

Figure 17: PMV-index 3 for people living in Building A (circle), B (square) and C (diamond) located in Stockholm; people aged 0-65 colored in green, people aged 65+ colored in orange

In general, results follow the same trend as in Malmö. It can be seen in figure 16, that people aged 65+ experience thermal discomfort to a higher amount, compared to younger people. While the hours of discomfort increase for people aged 65+ to an average of 55% for all buildings from P1 to P2, the increase to P3 is only 2% on average. For people aged lower than 65 years, same can be observed, with a high increase of hours between P1 and P2 with an average of 56% for all the buildings and 8% from P2 to P3. The high increase in discomfort hours from P1 to P2 highlights the fact, that projections of future climate will impact the indoor environment and increase the number of discomfort hours. A lower increase from P2 to P3 does not stand for a lower impact due to climate change, it only means that there are not many more hours when PMV-index is above 3, just the intensity increases. Since the results quantify the event of discomfort itself, summing up all the hours when PMV-index is over 3, the results might show a wrong picture. It is important to look as well at the temperatures, because different gradients of temperature have a different effect on the human health. If we compare the average temperatures of overheating hours in table 17, it can be clearly seen that the temperature increases on average higher from P2 to P3 compared to P1 to P2. Comparing the different building to each other, people below the age of 65 experience up to 30% less hours of feeling too hot with 105 h in P1, 235 h in P2 and 260 h in P3. People above the age of 65 experience under the climate projections 148 h in P1 and 353 h in P2 and P3. For building B the difference between the age groups is slightly higher with 36% less hours of discomfort for people aged below 65 and for building C it is 37%.

4.4.4 Extreme climate projections: Umeå

The indoor air temperature distributions of the building located in Umeå for future climate projections are shown using a boxplot in figure 18. The results show in general, that the future climate will impact the indoor environment of the building, with increasing temperatures indoors. The risk of extreme high temperatures occurs in building C and will increase in frequency in the future.

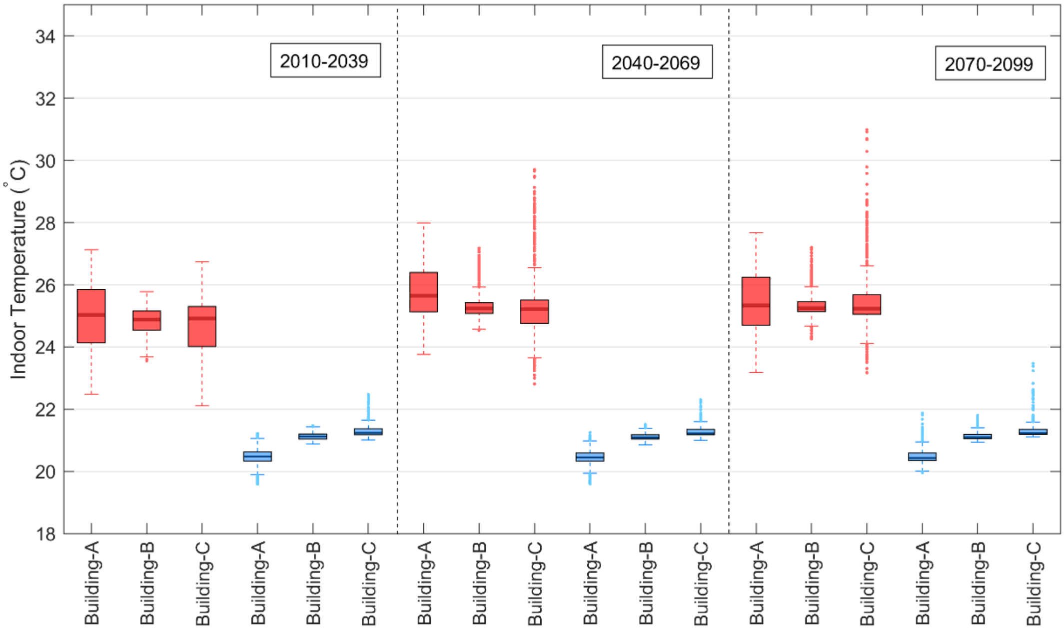

Figure 18:Indoor air temperature distribution for the EWY and ECY datasets for the three analyzed buildings in Umeå

It can be seen in the figure 18, that the temperature ranges of the buildings are similar to the once discussed before, Stockholm and Malmö. But compared to the two other cities, the temperatures are in general lower, showing that the south of Sweden is more susceptible towards climate change than the north in the next 100 years. Average temperatures in building A reach between 25.0°C and 25.7°C with a maximum temperature of 28.0°C. In comparison to that, average temperatures for the month of July are slightly lower in building B, with between 24.8°C and 25.4°C, and a maximum reaching 27.2°C. Similar average temperatures can be seen for the summer period in building C as in building B, but the maximum temperature can get as high as 31.0°C. Looking at the winter period, temperatures in building B and C are moderate with no extreme behavior. But in contrast to that, the temperatures in building A fall as low as 19.6°C even though the heating system was designed to maintain an indoor temperature of 21°C. The low temperatures could be a result of the high thermal heat losses though infiltration and the thermal envelope of building A, resulting in the fact that the heating system cannot make up for it.

Table 18 represents the number of hours exceeding the temperature threshold of 26°C indoors. Results show, that temperatures over 26°C will occur to a higher extend in building A, followed by building C and B, whereas building B has the lowest number of overheating hours.

Table 18: Number of overheating hours and their average temperature for Building A, B and C located in Umeå

	Building A		**Building B**		**Building C**	
	Hours above 26°C	T_{mean} (°C)	Hours above 26°C	T_{mean} (°C)	Hours above 26°C	T_{mean} (°C)
EWY-P1	158	26.5	0	-	8	26.3°C
EWY-P2	182	26.7	83	26.4	120	27.5°C
EWY-P3	209	29.3	83	26.5	162	27.2°C

Comparing these results to the other two cities, the lower number of hours indicates that the future climate projections will have a lower effect on indoor climate in Umeå compared to the south of Sweden, which is mainly since the outdoor temperatures during the summer period are rather moderate and around 3°C lower than in Stockholm and 4°C than in Malmö. If a 14 h occupancy schedule is considered for the buildings located in Umeå, the number of discomfort hours will result in even lower numbers than in Stockholm and Umeå. Highlighting the fact that most discomfort occur during the day and people that spent most of their times indoors are more susceptible to suffer from it. Building A will experience on average 65% less hours, building B 66% and building C up to 77%.

Comparing these results to the PMV-index 3 shown in figure 19, it can be clearly seen that contrary results are achieved. Out of the three buildings, building C resulted in the highest risk of hours outside of the PMV-range 3. Highlighting the fact, that building C is more susceptible to experience extreme high temperatures and increasing the risk that people living in that building will experience thermal discomfort. This is mainly due to the fact, that the PMV-index calculations take several factors, including the temperature into account and does not quantify the single event of overheating. Considering the full scale of the PMV-index as presented in table 25 in appendix 8.6 the accumulated hours outside of PMV-index +1, +2 and +3 resulted in the highest amount for building A. This shows that it is important to not only quantify the occurring event of discomfort, but also considering the temperature at when discomfort occurs. In general, results in figure 19 follow the same trend as in figure 18 and 17, showing that people aged 65+ are of higher risk to experience thermal discomfort compared to people below 65 years, with increasing numbers over the next 100 years.

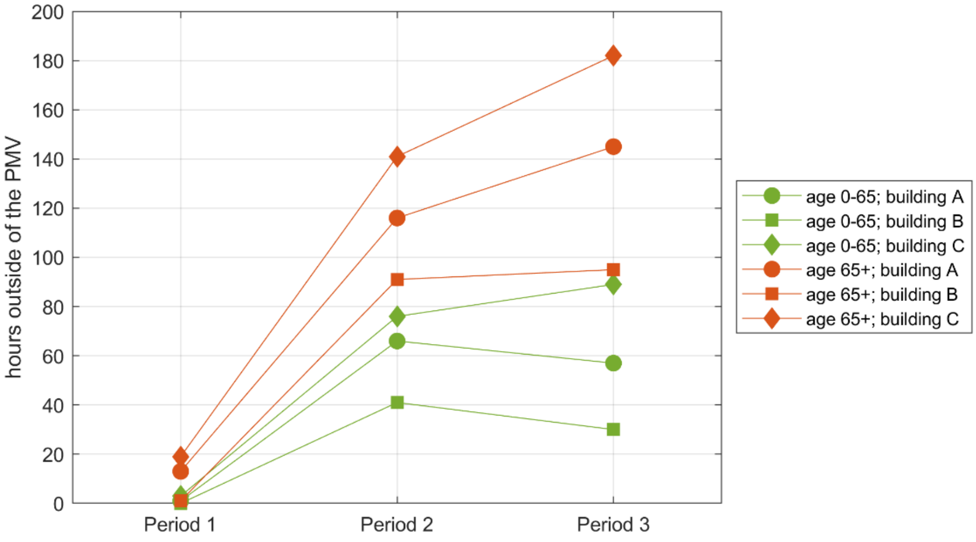

Figure 19: Figure 16: PMV-index 3 for people living in Building A (circle), B (square) and C (diamond) located in Umeå; people aged 0-65 colored in green, people aged 65+ colored in orange

4.5 Human Health assessment

In this chapter the results of calculated variations in future morbidity and mortality due to climate change are presented by using the region-specific temperature functions (RR) developed by Rocklöv et al. (2014). Three different methods were applied, and their results will be compared to each other to assess the impact of future climate projections on human temperature exposure. While calculations in Method A and B are based on outdoor temperatures, method C is using indoor temperatures accounting for the effect of different building constructions.

4.5.1 Method A

The variations in future morbidity and mortality due to climate change were estimated in method A by using the changes in mean average outdoor temperature of the extreme weather projection ECY and EWY. Figure 20 shows the estimated excess vulnerability for the three analyzed cities: Malmö, Umea and Stockholm, using future climate projections for the summer and winter period between 2010-2099. The results of excess mortality are expressed as a percentage of increase in regard to historical mortality (1997-2014) and morbidity (1992 and 2014), as presented in table 9. Based on the projections of excess vulnerability, an increase in the summer period and decrease in the winter period can be observed in figure 20.

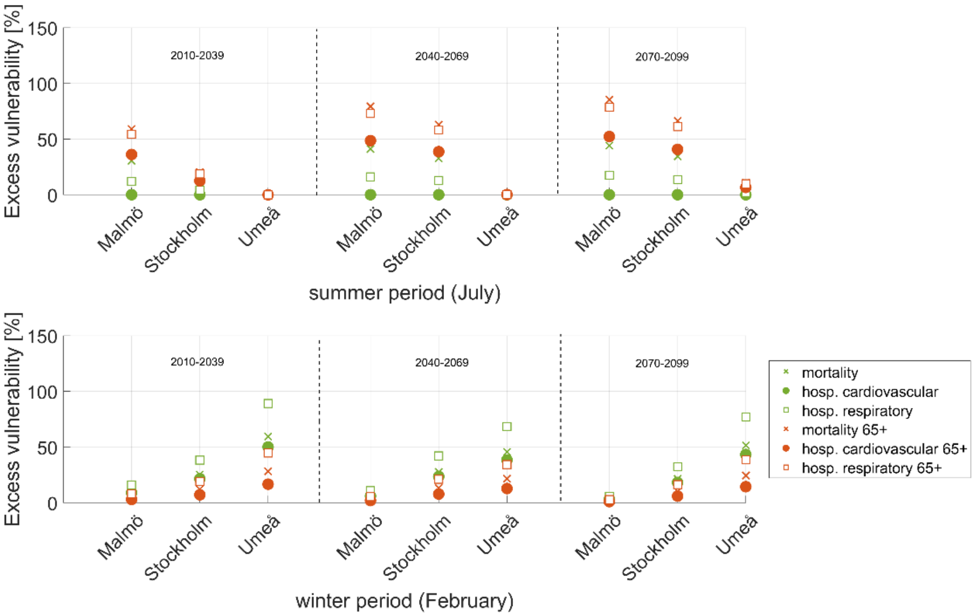

Figure 20: Calculated projections according to method A of excess mortality (cross), excess hospitalization due to cardiovascular disease (circle) and due to respiratory disease (square) for the cities Malmö, Stockholm and Umeå; people aged 0-65 colored in green, people aged 65+ colored in orange

The top plot of figure 20 presents the variations in excess vulnerability during the summer month July. Highest excess vulnerability can be observed in Malmö for all three periods, followed by Stockholm and Umeå. For the city of Umeå, excess vulnerability is estimated only for P3, which is mainly due to the reason, that the projected temperatures in Umeå are on average lower than the MMT of 20.7°C, with average temperature in July of 16.0°C in P1, 18.2°C in P2 and 19.6°C in P3. Therefore, the excess vulnerability due to heat exposure is relatively low compared to the two other cities, with 5% increase in mortality and around 2% increase in hospitalizations due to respiratory disease can be expected in P3 for people below the age of 65. For people aged 65+ the projections for P3 show an increase of mortality with 11% and 7% and 10% for hospitalizations due to cardiovascular and respiratory diseases. In contrast to that, temperature projections in Malmö show an average temperature of 21.4°C for P1, 23.°C for P2 and 23.5°C for P3, resulting in an increase of excess vulnerability though the next 100 years, witch a growing percentage in each period. The risk of mortality for people living in Malmö will increase with 30% to 44 % until the year 2100 for people below the age of 65, and for people aged 65+ the estimated risk will increase between 60% in P1 to 85 % in P3. An increase in hospitalization due to cardiovascular and respiratory diseases is estimated to increase with 36% to 53% for people below 65 and with 54% to 78% for people above 65 years. Cardiovascular hospitalizations have a minor impact on people between 0-65 and respiratory diseases have a small increase with 12% in P1, 16% in P2 and 17% in P3. Looking at the group of people below 65, the projected risk is lower, mainly due to a higher health status and lower historical mortality and morbidity (Rocklöv et al., 2014) For the city of Stockholm results indicate the same trend for excess vulnerability as for Malmö, but to a lower percentage, mainly due to lower temperatures outdoors. In general, the projections of future weather on heat related vulnerability show a higher impact on people above 65 years compared to people below. Same trends were found by Baccini et al. (2011), who analyzed the impact of heat on mortality in 15 European cities. The hospitalizations due to cardiovascular and respiratory diseases are higher for elderly, with a higher risk for cardiovascular disease compared to respiratory for all ages. This is mainly due to the fact, that heat exposure has a higher effect on cardiovascular diseases by a dysfunction of the thermoregulation mechanism, which is already lower for elderly due to aging (Spengler, 2012). The body responses with sweating to heat, causing a loss of fluid and salt, which can have strong consequences especially for people with pre-existing heart-diseases (Fonseca-Rodríguez et al., 2021).

Considering that the excess vulnerability was calculated regarding the weather dataset EWY, which represent the warmest conditions over a period of 30 years summed up in a 1-year dataset, it can be concluded that people living in Umeå are more resilient towards future outdoor temperature exposure compared to the two other cities, with Malmö resulting in the highest risk. Further, the south of Sweden is more susceptible to suffer from climate change as the results of future climate projections demonstrate. This is only true under the assumption, that the MMT of 20.7°C and the region-specific RR are same for all three cities. But since the human response to temperature exposure is location dependent and affected by autonomous human adaptation (Åström et al., 2016) and the RR values used in this projection of future excess vulnerability are based on a study conducted by Rocklöv et al. (2014) in the Stockholm region, it can be assumed that the results for Umeå are underestimated. People living in the northern climate are used to colder temperatures and might be more vulnerable towards high temperatures resulting in the fact that the MMT for Umeå is lower than 20.7 °C (Ye et al., 2012). Even though the results for Malmö are much higher compared to Stockholm, it can be assumed that the human temperature exposure is similar in those cities. Rocklöv and Forsberg (2010) analyzed the mortality of people aged 65+ for three regions in Sweden (mainly Malmö, Goteborg, and Stockholm) and concluded that the RR is similar in all cities. Even though the climate in those regions is different, the populations in those regions are rather homogenous in terms of health and standard of living. The region-specific temperature relations were used for Stockholm, to increase the field of study, and since this topic is relatively new, not many people have conducted the temperature exposure relation for different regions in Sweden.

Variation of future morbidity and mortality during the winter period are displayed in the bottom plot of figure 20. It can be mainly observed, that in contrast to the summer period, the excess vulnerability is decreasing with time, mainly due to increase in temperature and less frequently occurring extreme cold temperatures. In contrast to summer vulnerability the projections indicate a much higher risk during winter months (values presented in graph x10), showing that in countries located in cold climates the winter mortality will be dominant compared to summer mortality. Same findings were found in a study by Rocklöv and Forsberg (2008) who found a seasonal mortality pattern, with a higher effect in winter compared to summer. Other than in summer, people below 65 years (green markers) are of higher risk compared to people aged 65+ (orange marker), with higher risks for hospitalizations due to respiratory diseases compared to mortality. The difference in risk of excess vulnerability for the two age groups is about 50% for all cases, with higher risk in Umeå, followed by Stockholm and finally Malmö. This is mainly due to the fact, that people living in Umeå are exposed to colder temperatures than in Malmö. In a study by Fonseca-Rodríguez et al. (2021), on which some of the data used in this study are based on, same patterns were found under temperature intensity exposure. The author explained the high respiratory diseases in winter due to exposure to cold air, which can increase the number of viral respiratory infections, reduce the lung functions, and cause an inflammation of the bronchoconstriction's. Especially younger people are of higher risk due to behavioral factors. In winter, people spent due to the cold most of their times indoors and especially younger people and adults are more exposed to transmission of infections in places that are crowded (indoors). Other than expected, the risk of cardiovascular hospitalization is higher for people aged 0-65 compared to people aged 65+. Considering that the physiological response of a human body is to reduce heat loss is driven by the peripheral nervous system, which increases the workload of the heart rate to prevent feeling cold. Elderly people are more likely to have pre-existing cardiovascular diseases, resulting in a higher risk for elderly. Younger people can reach the hospital faster than older, causing a higher rate of death due to cardiovascular disease than hospitalizations between elderly and adults (Fonseca-Rodríguez et al., 2021).

4.5.2 Method B

Another commonly used method to assess the variations in future morbidity and mortality due to climate change is by using the changes in maximum daily outdoor temperature. Figure 21 presents the estimated excess vulnerability for Malmö, Umeå and Stockholm using the same future climate projections as in method A. Based on the projections of excess vulnerability, a general increase in the summer and winter period can be observed in figure 21.

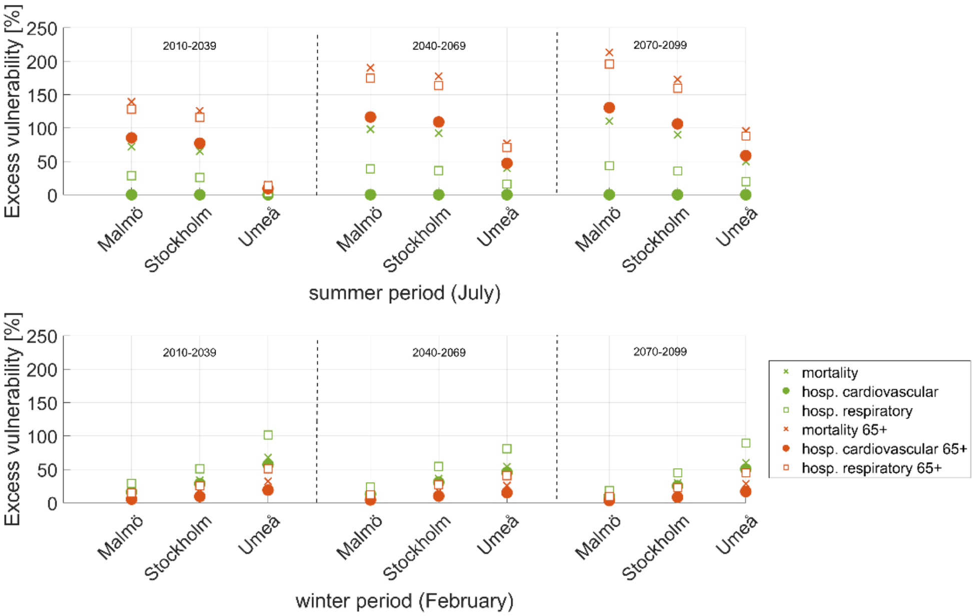

Figure 21: Calculated projections according to method B of excess mortality (cross), excess hospitalization due to cardiovascular disease (circle) and due to respiratory disease (square) for the cities Malmö, Stockholm and Umeå; people aged 0-65 colored in green, people aged 65+ colored in orange

Comparing the excess vulnerability projections of method A and B, a same pattern for the summer period can be seen. The excess vulnerability will increase in the future because of climate change, with higher effect for elderly people compared to people below the age of 65, just to a higher extend. In Malmö, projections for the summer period estimate an increase in mortality of 140%, 190% and 213% for people above 65 and to 72% 98% and 110% for people below 65 for P1, P2 and P3 respectively. This is on average an increase of 40% in mortality, when maximum daily temperatures are used for the estimations. For people below the age of 65 years the risk of excess mortality can increase up to 72% in P1, 98% in P2 and 110 % in P3 and is on average 40% higher compared to method A. Same pattern can be seen for risk hospitalizations due to cardiovascular and respiratory diseases and for the cities Stockholm and Umeå. Taking the difference in daily mean and maximum temperatures of the used weather data into account, the results are to be expected since the excess mortality calculations are based on temperatures. Projections of maximum temperatures in Malmö can get as much as 11°C higher than the mean daily temperature, with maximum reaching up to 34.8°C. Same accounts for Stockholm and Umeå, where maximum temperatures reach up to 35.0°C and 30.7°C respectively. This higher variability in extreme temperatures stands for the higher projections of summer excess vulnerability.

Interestingly, the projections in excess vulnerability showed different patterns for the three cities using the coldest daily temperatures. Results still indicate the same trend, with higher risks for people below 65 years and higher impact on hospitalizations due to respiratory diseases compared to mortality and hospitalizations due to cardiovascular diseases. In Malmö, the trend follows a decrease of mortality and hospitalizations over the three periods for both age groups. In contrast to that, the excess vulnerability in Stockholm increases from P1 to P2, followed by a decrease in P3. In Umeå opposite projections can be observed, with a slightly decrease in excess vulnerability from P1 to P2, followed by an increase from P2 to P3. This can be mainly explained by the daily temperature variability of the future climate projections. Accounting for the daily variability of the ECY datasets, the projections might show a false picture because they take daily variabilities into account. Comparing the coldest temperatures in the three cities of the ECY future climate projections, table 13, temperatures can fall as low as -19.9°C in Malmö, -25.1°C in Stockholm and -40.0°C in Umeå. It is important to mention here that the ECY weather data represents the coldest weather over a period of 30 years compromised in one year, and it is most likely impossible, that all the coldest events over 30 years will occur consecutive during one month. Therefore the projected excess vulnerability in figure 21 is to be treated with cautious, because they represent overestimations and consider single events, when accounting for daily minimum temperatures. Gosling et al. (2009), found similar results in his study, when comparing the excess mortality when using daily maximum/ minimum temperatures compared to daily mean temperatures. Projecting the excess vulnerability with the use of daily maximum/ minimum temperatures account for a higher variability of temperature intensities compared to mean daily temperatures.

4.5.3 Method C

The impact assessment of future climate on morbidity and mortality due to exposure to indoor temperatures of three different building construction types was estimated for the city of Malmö, Umeå and Stockholm. Figure 22 represents the projected excess vulnerability for each city and the two groups of people. Projections indicate in general an increase in vulnerability, with a higher extend in Malmö, followed by Stockholm and Umeå. Figure 22 only represents the excess vulnerability during the summer period. The impact assessment during the winter period was neglected, since the indoor temperature distribution, as shown in figure 14, 16 and 18, showed a moderate distribution.

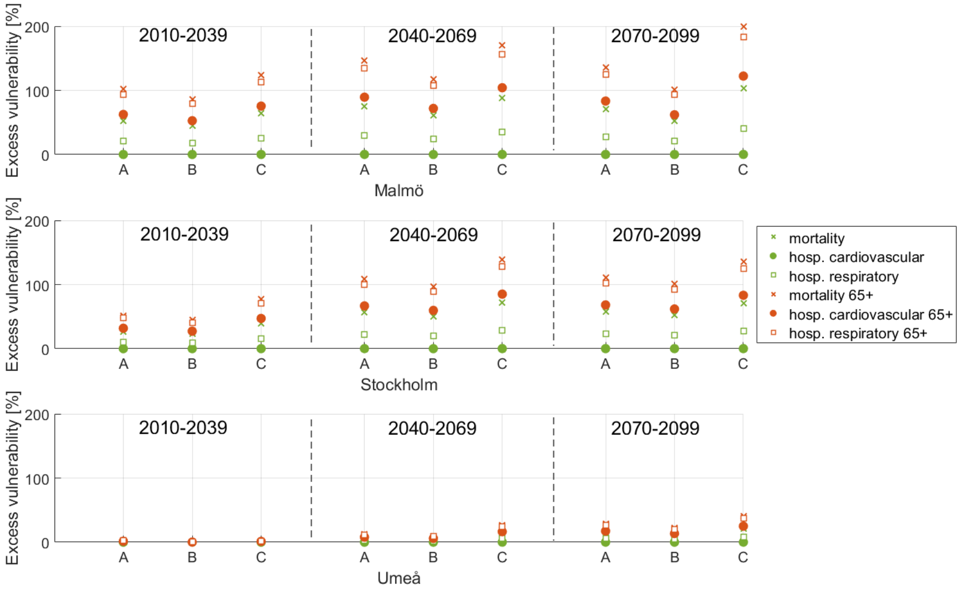

Figure 22: Calculated projections according to method D of excess mortality (cross), excess hospitalization due to cardiovascular disease (circle) and due to respiratory disease (square) for the cities Malmö, Stockholm and Umeå; people aged 0-65 colored in green, people aged 65+ colored in orange

Comparing the projection of excess mortality between the cities, it can be clearly seen, that the people living in the south of Sweden have a higher risk of experiencing excess morbidity and mortality compared to the north, with higher numbers in Malmö compared to Stockholm. In general, projections of excess vulnerability indicate that people aged 65+ are of higher risk compared to people below 65 years. Similar results were found with method A and B using outdoor temperatures, which is mainly since elderly people are more sensitive towards extreme temperatures due to a decreasing function of their thermoregulation system (Spengler, 2012). Even though these projections are overestimations, it is important to consider the higher risk for older people, since they are most likely to spent more time indoors compared to younger people and adults, which spent most of their time during the day outside of the building they live in (Bundle et al., 2018). Comparing the estimations for the different buildings located in Malmö, people living in a new building have a 19.3% higher mortality rate in P1 compared to building B, the retrofit with the lowest risk, with increasing difference in the following periods, mainly 27.3% higher risk in P2 and up to 50.9% in P3. The effect on mortality of building A, the original state of the building, is not as much higher compared to building B as A, but the risk of higher mortality in about 9% in P1, 14.8% in P2 and 18.0% in P3. Same trend can be seen for the hospitalizations due to cardiovascular and respiratory diseases for both age groups. This result is unsurprising, when looking at the estimated temperatures in each building presented in table 12 and 13. Comparing the temperature anomalies of each building and city to each other and considering the days when $T_{heat,effective}$ exceeds T_{heat} during the summer, it can be clearly seen that building C has the highest percentage as well as range of temperature anomaly. The temperature anomaly describes the difference to the average temperature of each building in each city over the summer period. In Malmö, the average range of temperature anomaly is between +1.6 to +3.7 for building C, +2.3 to +3.2 for building B and +1.7 to +3.1 building A. Percentage of days when $T_{heat,\ effective}$ exceeds T_{heat} is the lowest in building A, with 35-42%, followed by building B with 84% and building C with 93-97%. Even though building B has almost as many days when $T_{heat,\ effective}$ exceeds T_{heat}, the temperature intensity is not as high which is indicated by the lower range and lower number of temperature anomaly. This could be a result of the energy-efficient measures in building C and higher building airtightness in general, as described in the previous chapters. Because building B has a lower number of temperature anomaly, it shows that the thermal mass of the construction plays a major role in temperature distribution and its intensity, as the results indicate.

The projections of excess vulnerability in the two other cities show similar results and trends as shown in Malmö, with the difference of having a lower impact, mainly due to the lower temperature distributions indoors and outdoors due to their location, resulting in the fact that $T_{heat,\ effective}$ exceeds T_{heat} to a lower percentage during the summer period compared to Malmö. While $T_{heat,\ effective}$ exceeds T_{heat} between 55% and 68% in Stockholm, the percentage of days is even lower with 3% to 42% in Umeå, with higher percentage in building C, followed by A and B. These results indicate that people living in Umeå are of lower risk to experience an impact on their health due to future climate projections, when considering the time, they spent indoors. The health impact assessment here is based on the EWY dataset, if typical weather projections would be considered, it can be estimated that the impact is even lower in the cities, with the probability of 0% of risk for people living in these three building in Umeå.

Table 19: Temperatures during summer for the three analyzed buildings A, B, C: results based on temperature distribution for EWY climate projections

		P1			**P2**			**P3**		
		A	B	C	A	B	C	A	B	C
Malmö	$T_{max,daily}$ (°C): mean (min, max)	25.5 (20.7, 33.3)			26.9 (21.9, 31.5)			27.7 (23.9, 34.4)		
	% of days in July when $T_{max,out}$ exceeds T_{heat} (20.7 °C)	90%			97%			97%		
	Building specific $T_{mean,daily}$ (°C)	26.57	26.82	26.52	26.01	26.42	26.36	26.52	27.18	25.84
	Building specific ΔT: regional T_{mean} (°C) (min, max)	1.7 (-1.6, 7.5)	2.3 (-1.0, 8.1)	1.6 (-1.5, 7.6)	2.5 (-1.5, 6.4)	2.9 (-1.1, 6.8)	2.1 (-1.8, 6.0)	3.1 (-1.3, 7.8)	3.2 (-1.2, 8.0)	3.7 (-0.7, 8.5)
	% of days in July when $T_{heat,effective}$ exceeds T_{heat}	42%	84%	93%	35%	77%	84%	42%	84%	97%
Stockholm	$T_{max,daily}$ (°C): mean (min, max)	24.5 (17.7, 31.9)			26.4 (18.5, 33.8)			26.4 (21.1, 35.0)		
	% of days in July when $T_{max,out}$ exceeds T_{heat} (20.7 °C)	74%			88%			79%		
	Building specific $T_{mean,daily}$ (°C)	25.48	25.39	25.84	26.38	26	26.8	26.62	26.13	26.81
	Building specific ΔT: regional T_{mean} (min, max)	1.2 (-1.1, 2.9)	0.9 (-0.1, 2.3)	2.0 (-0.3, 6.3)	1.6 (-0.9, 5.3)	1.1 (-0.6, 3.6)	2.5 (-1.3, 8.0)	1.4 (-1.1, 4.7)	0.9 (-0.8, 3.6)	2.0 (-1.4, 7.1)
	% of days in July when $T_{heat,effective}$ exceeds T_{heat}	65%	61%	68%	55%	65%	68%	61%	61%	68%
Umeå	$T_{max,daily}$ (°C): mean (min, max)	20.1(16.8, 23.6)			23.0(18.5, 27.8)			23.9 (20.5, 30.7)		
	% of days in July when $T_{max,out}$ exceeds T_{heat} (20.7 °C)	52%			67%			59%		
	Building specific $T_{mean,daily}$ (°C)	24.78	24.61	24.47	25.5	25.11	25.22	25.24	25.17	25.3
	Building specific ΔT: regional T_{mean} (°C) (min, max)	0.9 (0.0, 2.4)	0.3 (0, 1.2)	0.6 (0.0, 2.3)	1.1 (0, 2.5)	0.6 (-0.1, 2.1)	1.3 (-0.1, 4.5)	1.1 (-0.7, 2.5)	0.7 (-0.1, 2.1)	1.5 (-0.2, 5.7)
	% of days in July when $T_{heat,effective}$ exceeds T_{heat}	13%	3%	6%	39%	32%	35%	45%	35%	42%

The projections of excess vulnerability in figure 22 indicate, that the climate change mitigation strategy of building energy efficient housing can have a negative impact on the health of a human. Even though the retrofit case, building B, resulted in the lowest risk, with a higher insulation and airtightness as an energy-efficient measure, an even higher airtightness of the building envelope, like in building C, can increase the risk massively and cause undesirable effects on the human health. Therefore, it is important to implement energy saving measures with care and weight in more factors than energy saving. Further, the effect of thermal inertia is important specially to reduce the temperature fluctuations, which increase the temperature exposure. The fact that most of the new constructions are designed with the aim to reduce the carbon footprint, concrete structures are exchanged with timber-frame structures, to reduce the environmental footprint (Sinha et al., 2016). This results in newly built buildings having a lower thermal inertia, increasing the risk for temperature fluctuations indoors and creating a worse indoor environment

Similar results to the one presented in this study have been found in studies conducted by Taylor et al. (2018) on who's the assessment is based on. Taylor et al. (2018) found a slightly increase in mortality risk because of energy-efficient measures conducted on the English building stock, due to increase in temperature exposure for humans indoors. Same as in Taylor et al. (2018) study, the projections for future heat-related morbidity and mortality is based on an exposure-response function, which were derived using outdoor temperature, which results in the assumption, that risks due to outdoor temperature exposure account to the same extend when using indoor temperatures. Nonetheless, the human vulnerability during the winter period showed extreme high results compared to summer mortality, and since the winter mortality is predominant in cold climates, it is important that energy-efficient measures are implemented. It is important to find the balance between winter and summer discomfort and risk.

4.6 Overall results and discussion

Projections of future energy demand for all three buildings indicated, that it is important to implement energy efficient measures to be able to achieve a lower heating demand of buildings. Up to 10% of the heating demand can be reduced under TDY projections, with 25% lower demand for retrofit design and 62% for a new constructed building. But the implementation has to be conducted under regard to the impact on humans and their health and assure a good indoor environment. Comparing the results of indoor comfort assessment and excess vulnerability calculations using indoor temperatures of three different construction types, contrary results were found when assessing the thermal comfort and health impact. While the thermal comfort assessment in chapter 4.4. indicated that building A has highest risk of overheating, followed by building C and B, the results of the health impact assessment show the highest risk in building C, followed by building A and finally building B. This is mainly due to the fact, that when assessing the discomfort hours, the actual event of overheating is quantified, without consideration to the temperature intensity, when overheating occurs. Even though building C resulted in the highest indoor temperatures compared to the other buildings in all cities, building A counted the highest number of overheating. The projections of excess vulnerability using indoor temperatures (method C) take the actual temperature intensity into account, resulting in the fact that people living in building C have the highest risk to experience a health impact due to exposure to high temperatures compared to the two other buildings.

The health impact assessment in this study is based on single temperature events and accounts for their intensity rather than duration. Several studies have analyzed the effects of extreme temperatures over several days, mainly heat and cold waves, and compared the results of health outcomes due to temperature intensity and duration to each other. Rocklöv et al. (2014) compared the susceptibility to mortality from temperature intensity and heat and cold wave duration and found that different human groups stratified by age and sex showed different susceptibility to different types of exposure, mainly temperature intensity and duration. Same as in this thesis, increased temperatures were associated with increasing risk for elderly people, but when taking heat duration into account, contrary results were found, with higher risk for the younger population, below the age of 65 years. During the winter period, Rocklöv et al. (2014) found in the study, that cold waves event increases the risk for elderly, while single extreme temperatures in winter increase the health impact on younger people. Interestingly, opposite results are found when taking temperature intensity or duration into account, with contrary results. This is mainly due to the fact, how the human body reacts to temperature exposure and highlights the fact, that both, temperature intensity and duration are important risk factors for humans in the future.

This study involved a large number of simplifications and assumptions, which could lead to over- and underestimations of the projected risks. Usually energy-efficient measures of buildings are combined with housing adaptation to reduce overheating risk, such as implementation of shutters or air conditioning. This was neglected in this study and only an opening of windows was considered. To recreate the behavior of the occupants better, it was assumed that windows are opened, when the indoor temperatures exceed 26°C. This assumption neglects the fact, that the perception of elderly people is less sensitive towards extreme temperatures, leading to the fact that elderly might not recognize their exposure as fast as adults and do not open the windows (Ormandy and Ezratty, 2016). In a study conducted by Taylor et al. (2018) the effect of closed windows on heat-related mortality showed an increase of 29-64% in different building types, when the windows were closed. This shows that elderly is more susceptible to suffer from temperature-related mortality due to their health state. In the same study it was shown, that external shutters as housing adaption measure could reduce the heat-related mortality with up to 37-43%.

The application of the heat-related vulnerability model in this study was derived on historic data of Stockholm and to increase the size of results, this model was applied for health impact assessment in Malmö and Umeå., which might result in a false estimation of risks due to different climatic conditions in the three locations. Further, the exposure-response function is derived for outdoor temperatures, and it is assuming that is has the same effect for indoor temperatures. This is probably not true, because there are multiple factors that significantly impact the indoor environment, inducing indoor heat and solar gains. Adaptive behavior is another source that could alternate the effect indoors, considering the fact that people spending time indoors have a wider range of possibilities to cope with the extreme heat, by for example taking of clothes, opening the window, turning on AC, taking showers (Taylor et al., 2021). Further, no changes in demographic distribution, housing stock or population adaptation were accounted for, resulting in the fact that the results of this thesis show a trend of future human health impact rather than predict the extend of health outcomes.

5 Conclusion

This study analyzed the impacts of future climate on indoor thermal comfort and conducted a human health impact assessment due to future temperature exposure. Considering that one of Sweden's national goals to fight climate change includes a nearly zero-emission building stock (NZEB) by 2050, by transforming the buildings into highly energy efficient buildings, and the fact that future climate projections predict an average temperature increase with up to 2°C by the 2020's, 2-3°C by the 2050's and 3-5°C by the 2080's (Swedish Commission, 2007), humans are of greater risk to be exposed to higher temperatures in the future compared to the past climate. Higher temperatures indoors due to energy efficient buildings are mainly a result of insufficient air exchange resulting from a minimized infiltration and reduced heat loss rate due to the installation of thicker insulation, which are both measures to reduce the energy consumption (Fisk, 2015).

The health impact due to temperature exposure in typical Swedish residential buildings was assessed for three different construction types of the same building using future climate projections for Malmö, Stockholm and Umeå. Projections of the indoor temperatures under typical (TDY) and extreme climate data (EWY, ECY) indicated the highest risk of overheating in the original construction of the building (building A), followed by the new design (building C) and lowest overheating risk in the retrofit building (building B). Malmö, located in the south of Sweden, is more susceptible for overheating potential compared to Stockholm and Umeå. Under TDY projections, no overheating potential was detected for Umeå, while the extreme climate projections showed high overheating for all cities, with increasing effects in the future. For all cases, elderly people are of higher risk to experience thermal discomfort indoors. Indoor comfort simulations showed, that elderly experience on average 10% more discomfort compared to people aged 0-65 living in Malmö and up to 12% living in Stockholm and Umeå. Considering that elderly and sick people are most likely to spent most of the day inside the building, the risk for experiencing discomfort increases. Accounting for a 14-h schedule, the discomfort hours were reduced by up to 45% in Malmö, 56% in Stockholm and up to 69% in Umeå, highlighting the fact that the risks differentiate between human groups and increases for people that spent more time in the buildings. Not only due to the fact that elderly and sick people are more vulnerable towards extreme warm temperatures, but also due to behavioral differences. Projections of the health impact due to temperature exposure of the future climate conditions showed likewise highest risk for elderly people with higher grade of risk in Malmö compared to Stockholm and Umeå. Highest risk was found to be on heat-related mortality, followed by hospitalizations due to respiratory and cardiovascular diseases. Same trends are observed when comparing outdoor and indoor temperature exposure with different extends of risk due to temperature intensity. Projecting the excess vulnerability with the use of daily maximum temperatures compared to mean temperatures, account for a higher variability of temperature intensities and thus result in higher projected risk.

Contrary to the findings of indoor comfort analysis, the health impact assessment due to indoor temperature exposure indicated highest risk for people living in building C, the new design, compared to the two other constructions. This result highlights the importance of accounting for temperature intensity, rather than the event of when a threshold is exceeded, because extreme temperatures increase the risk of human health impact. Although projections of indoor environment in building A indicated higher numbers of overheating, the indoor temperature is higher in building C, with more frequent accruing extremes. Under TDY projections, temperatures indoors reach up to 28.6°C degrees in building A and 32.5°C building C, without accounting for housing adaptation. Projections of extreme weather conditions reached a maximum indoor temperature of 32.4°C and 34.4°C, with increasing extremes in within the next century. This is an important finding considering the fact that the Swedish national goal is to reach a carbon neutral building stock until 2045, which includes energy-efficient measures to reduce the heating demand and the use of building materials with a lower carbon emissivity such as wood. Results of future heating demand indicated the heating demand can be reduced with about 60% under typical and extreme future climate conditions for the new construction compared to the two other buildings, with the downside of increasing the human health impact due to temperature-exposure as a result of increased airtightness of the building envelope and reduced thermal mass of the new construction. Therefore, it is important to account for the impacts of climate change on humans and their health when constructing new buildings. The design should decrease the energy demand, without compromising the thermal comfort and thus increase the risk for humans.

6 Future research

Further research is needed in human health impact assessment due to indoor temperature exposure, when housing adaptation is considered. Passive and active measures to mitigate thermal discomfort such as different shading strategies as well as building ventilation can affect the energy demand as well as temperature exposure and alternate the risks for human health. Other factors which increase the risk of overheating of buildings such as orientation, height of building, building type and location could show interesting results. Accounting for human adaptation to temperature as well as demographic changes within the population of Sweden could be part of future studies and assess predictions rather than projections of future human health impact.

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8 Appendix

8.1 Calculating the Average U-Value according to BBR 29

The U_m was calculated according to equation 9, taken from BBR 29.

$$U_m = \frac{\sum_{i=1}^{n} U_i A_i + \sum_{k=1}^{m} l_k \psi_k + \sum_{j=1}^{P} x_j}{A_{om}} \tag{9}$$

Where U_i is the heat transfer coefficient for building component i (W/m^{2}K), A_i is the area of the building component i, l_k is the length of the linear bridge and ψ_k is the heat transfer coefficient for the linear thermal bridge k. x_j is the heat transfer coefficient for the point thermal bridge j (W/K) and A_{om} is the total area of the building envelope. For simplification, it was assumed that cold bridges lower the total U-value by 30%.

8.2 Calculating the primary energy demand for heating

The Swedish building regulation sets a threshold for a primary energy number (EP_{pet}) for each building type. The EP_{pet} is calculated according to equation 10:

$$EP_{pet} = \frac{\left(\frac{E_{uppv,i}}{F_{geo}} + E_{kyl,i} + E_{tvv,i} + E_{f,i}\right) * VF_i}{A_{temp}} \tag{10}$$

Where EP_{pet} is the primary energy number, $E_{uppv,i}$ is the energy demand for heating, F_{geo} is the geographical adjusting factor, $E_{kyl,i}$ is the energy demand for cooling, $E_{tvv,i}$ is the enrgy demand for DHW, $E_{f,i}$ is the energy demand for electricity, VF_i is the energy carrier and A_{temp} is the heated floor area. This formula was converted to receive the primary energy demand for heating and DHW, and calculated for each location according to equation 11:

$$E_{uppv,i} = \left(\frac{EP_{pet} * A_{temp}}{VF_i} - E_{kyl,i} - E_{tvv,i} - E_{f,i}\right) * F_{geo} \tag{11}$$

Where EP_{pet} is 75 kWh/m^2, VF_i is 0.7 for district heating and F_{geo} is 0.8 for Malmö, 1.0 for Stockholm and 1.3 for Umeå according to BBR 29. A_{temp} is 1420m^2, $E_{kyl,i}$ and $E_{f,i}$ is zero and $E_{tvv,i}$ is 25 (35 500) kWh/m^2 (according to BEN2). Table 20 represents the results of the calculated primary energy demand for heating of each location.

Table 20: Heating demand threshold for the three locations (Malmö, Stockholm and Umeå) according to the Swedish Building Regulation BBR 29

Location	**Primary energy demand heating (kWh/m^2)**	**Primary energy demand DHW (kWh/m^2)**	**Total primary energy demand (kWh/m^2)**
Skåne (Malmö)	66	25	91
Stockholm	82	25	107
Västerbotten (Umeå)	106	25	131

8.3 Period of record of past climate data for each city

Table 21: Past climate data year of record for each month of the year for the three locations: Malmö, Stockholm, Umeå

	Malmö (2004 - 2018)	Stockholm (2002 - 2019)	Umeå (2004 - 2018)
January	2017	2009	2006
February	2004	2005	2017
March	2009	2002	2004
April	2004	2002	2018
May	2004	2008	2011
June	2004	2007	2005
July	2005	2005	2016
August	2007	2019	2005
September	2014	2004	2018
October	2008	2007	2018
November	2017	2019	2012
December	2007	2014	2014

8.4 Monthly average temperature

Table 22: Monthly average temperatures of the climate datasets TDY, EWY, ECY for P1 (2010-2039), P2 (2040-2069), P3 (2070-2099) for the three locations: Malmö, Stockholm, Umeå

	January	February	March	April	May	June	July	August	September	October	November	December	Yearly mean	Minimum	Maximum
Malmö	2.4	2.1	3.8	7.1	10.8	15.0	17.0	17.0	14.1	10.4	6.6	3.9	9.2	-6.7	-26.6
	2.8	3.1	4.7	7.5	11.4	15.3	17.8	17.5	14.9	11.3	7.3	4.7	9.9	-7.8	27.1
	4.0	3.9	5.3	8.2	12.1	16.3	18.4	18.3	15.6	11.6	7.9	5.5	10.6	-8.0	30.9
	6.7	7.0	7.8	10.5	14.1	20.1	21.4	21.3	17.9	14.4	10.1	8.4	13.3	1.1	33.8
	7.1	8.4	8.4	12.5	15.5	21.0	23.1	22.4	19.2	15.2	10.9	9.2	14.5	-0.2	32.3
	10.2	8.8	9.9	12.3	17.4	22.6	23.5	23.4	20.2	16.2	12.7	9.9	15.6	1.9	34.8
	-5.3	-3.5	-3.9	2.5	7.1	10.9	14.3	14.4	11.4	5.5	1.4	-3.3	4.3	-19.9	21.9
	-6.7	-2.6	-2.4	2.7	7.8	11.0	14.6	14.1	11.6	7.5	2.6	-1.5	4.9	-18.1	20.5
	-3.0	-1.8	-1.5	3.0	8.0	11.9	14.3	14.2	12.2	6.4	3.0	-0.5	5.6	-14.3	20.2
Stockholm	-1.7	-2.8	0.3	4.7	9.6	14.2	16.4	15.8	12.2	7.8	3.1	-0.3	6.7	-15.8	26.7
	-1.2	-0.9	1.8	5.6	10.3	14.8	17.2	16.4	13.0	8.3	3.8	0.9	7.6	-17.7	25.3
	-0.3	0.2	2.5	6.5	10.9	15.5	18.0	17.4	13.7	9.1	4.7	1.3	8.3	-12.1	29.8
	2.3	2.3	5.0	9.2	13.2	18.0	19.8	20.2	15.8	11.8	8.2	3.0	10.8	-1.4	31.9
	4.9	5.1	6.1	10.9	15.4	19.4	21.9	20.4	18.0	13.9	8.4	6.4	12.6	-2.9	33.8
	6.6	6.8	8.5	11.0	15.8	21.2	22.7	22.2	18.2	13.8	10.2	7.5	13.7	-0.7	35.0
	-8.3	-10.4	-10.1	-3.6	5.4	10.7	13.5	12.8	8.4	1.6	-3.6	-9.6	0.6	-25.1	19.8
	-12.1	-11.5	-9.6	-2.5	6.7	10.4	14.0	13.2	8.8	4.0	-1.4	-8.6	1.0	-23.3	18.9
	-9.5	-9.9	-5.6	-2.2	6.5	11.6	13.7	13.2	9.1	4.1	-1.1	-6.6	2.0	-20.1	23.2
Umeå	-9.2	-9.5	-6.6	-0.9	6.2	11.2	13.4	12.3	8.5	3.8	-2.2	-7.4	1.7	-26.9	21.6
	-6.3	-6.9	-4.2	0.7	7.0	11.7	13.9	12.8	9.1	4.1	-1.2	-4.9	3.0	-28.1	23.1
	-6.7	-6.2	-3.4	1.9	7.6	12.6	14.9	13.7	9.6	4.9	0.2	-5.0	3.7	-22.9	23.5
	-15.9	-14.7	-6.3	2.4	9.2	14.6	16.0	15.8	12.1	6.6	-1.4	-10.2	2.4	-14.1	23.9
	-0.6	-0.2	1.4	6.4	10.9	15.7	18.2	16.3	14.4	11.2	5.2	1.5	8.4	-17.2	27.8
	3.0	2.9	4.5	7.6	12.5	17.1	19.6	19.0	15.4	12.5	6.8	4.3	10.5	-6.3	30.7
	-20.1	-20.0	-15.4	-8.4	0.8	7.6	11.8	8.8	5.6	-0.8	-9.9	-17.8	-4.7	-40.1	18.5
	-20.7	-20.7	-15.8	-8.8	2.8	7.7	10.9	9.7	5.2	-1.8	-8.9	-14.6	-4.5	-31.4	21.5
	-18.3	-18.1	-14.6	-7.7	3.1	8.5	10.9	8.9	4.3	-0.6	-9.4	-15.9	-4.0	-30.7	20.5

8.5 Indoor temperature distribution using TDY projection

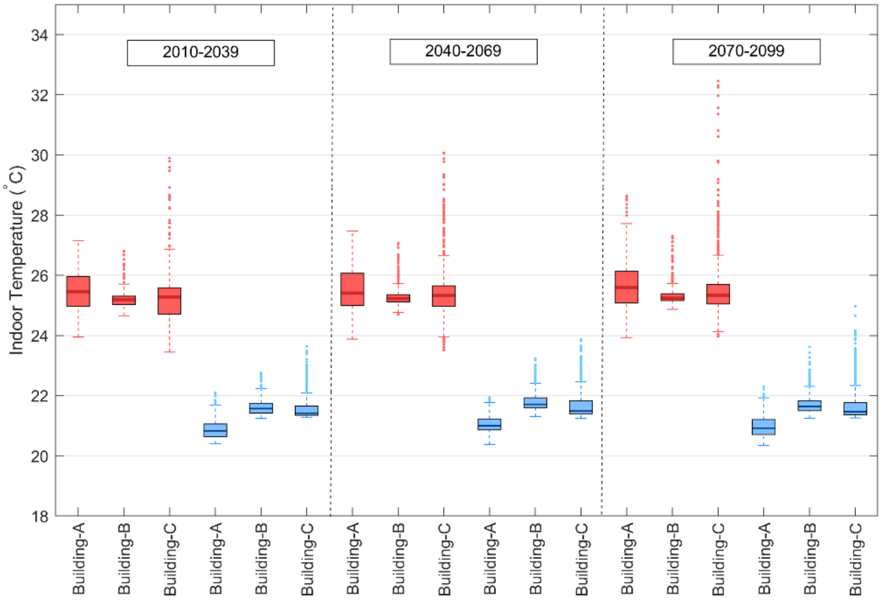

Figure 23:Indoor air temperature distribution for TDY dataset for summer period (red) and winter period (blue) for the three analyzed buildings in Malmö

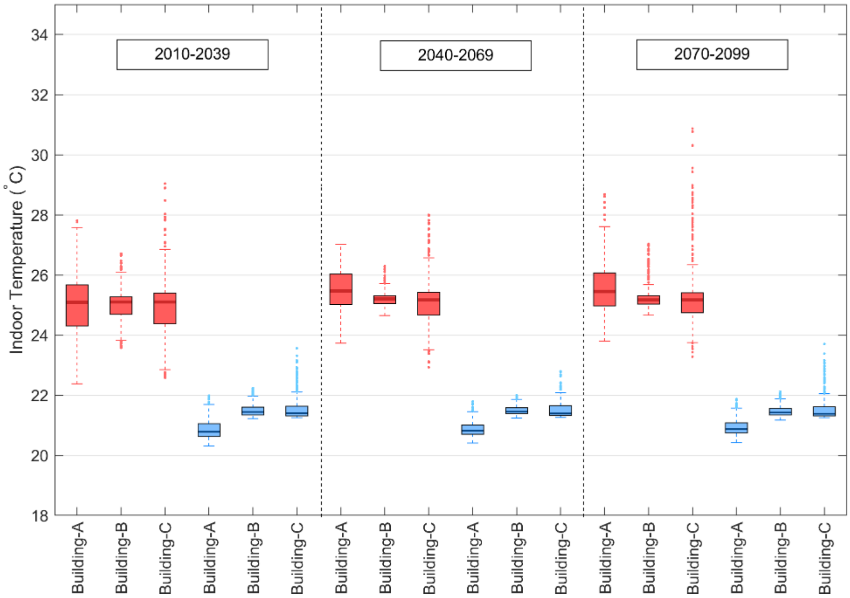

Figure 24:Indoor air temperature distribution for TDY dataset for summer period (red) and winter period (blue) for the three analyzed buildings in Stockholm

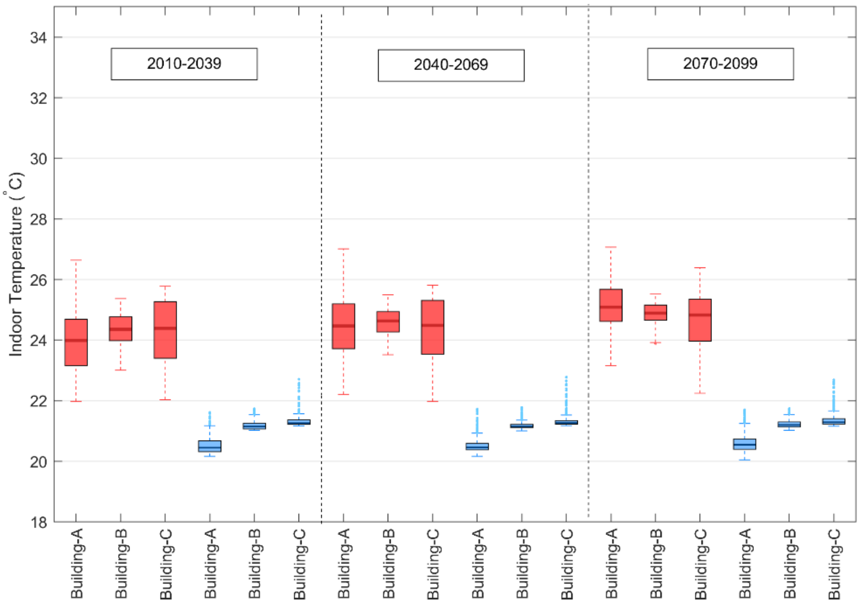

Figure 25:Indoor air temperature distribution for TDY dataset for summer period (red) and winter period (blue) for the three analyzed buildings in Umeå

8.6 Results of PMV-index on full scale

Table 23: Full range of PMV/index scale for month of July in Malmö, using EWY datasets

		Period 1			**Period 2**			**Period 3**		
	PMV-Index	A	B	C	A	B	C	A	B	C
Malmö (0-65)	3	226	192	173	362	287	290	312	232	280
	2	20	32	32	77	91	61	99	103	59
	1	135	148	172	174	228	232	227	282	246
	-1	0	0	0	0	0	0	0	0	0
	-2	0	0	0	0	0	0	0	0	0
	-3	0	0	0	0	0	0	0	0	0
	∑hours	**381**	**372**	**377**	**613**	**606**	**583**	**638**	**617**	**585**
Malmö (age 65+)	3	282	254	250	475	419	438	408	351	410
	2	475	36	61	111	133	126	119	143	71
	1	408	446	307	143	192	157	214	250	259
	-1	0	0	0	0	0	0	0	0	0
	-2	0	0	0	0	0	0	0	0	0
	-3	0	0	0	0	0	0	0	0	0
	∑hours	**1165**	**736**	**618**	**729**	**744**	**721**	**741**	**744**	**740**

Table 24: Full range of PMV/index scale for month of July in Stockholm, using EWY datasets

		Period 1			**Period 2**			**Period 3**		
	PMV-Index	A	B	C	A	B	C	A	B	C
Stockholm (0-65)	3	105	56	124	235	195	216	260	232	214
	2	55	53	35	81	66	53	55	43	61
	1	165	161	101	184	229	223	268	305	293
	-1	0	0	0	0	0	0	0	0	0
	-2	0	0	0	0	0	0	0	0	0
	-3	0	0	0	0	0	0	0	0	0
	Σhours	**325**	**270**	**260**	**500**	**490**	**492**	**583**	**580**	**568**
Stockholm (65+)	3	148	109	201	353	301	333	352	313	289
	2	89	85	42	111	138	125	119	119	205
	1	315	393	289	207	278	204	251	312	254
	-1	0	0	0	0	0	0	0	0	0
	-2	0	0	0	0	0	0	0	0	0
	-3	0	0	0	0	0	0	0	0	0
	Σhours	**552**	**587**	**532**	**671**	**717**	**662**	**722**	**744**	**748**

Table 25:Full range of PMV/index scale for month of July in Umeå, using EWY datasets

		Period 1			**Period 2**			**Period 3**		
	PMV-Index	A	B	C	A	B	C	A	B	C
Umeå (0-65)	3	1	0	3	66	41	76	57	30	89
	2	9	2	9	31	34	21	68	57	40
	1	130	152	158	234	291	222	308	388	308
	-1	0	0	9	0	0	0	0	0	0
	-2	9	0	29	0	0	3	0	0	0
	-3	71	2	59	0	0	21	5	0	8
	Σhours	**220**	**156**	**267**	**331**	**366**	**343**	**438**	**475**	**445**
Umeå (65+)	3	13	1	19	116	91	141	145	95	182
	2	45	34	53	104	82	95	134	182	163
	1	290	376	308	351	477	275	328	429	242
	-1	0	0	15	0	0	0	43	0	0
	-2	0	0	31	0	0	7	0	0	0
	-3	0	0	61	0	0	30	4	0	11
	Σhours	**348**	**411**	**487**	**571**	**650**	**548**	**654**	**706**	**598**

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