Low-Energy Solution for a High Temperature Problem

How effective are passive and low-energy cooling strategies in providing heat resilience in existing residential buildings in the Netherlands in a user-centred and resource efficient manner?

P2

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1. RESEARCH FRAMEWORK

1.1 Background

Climate change and the Urban Heat Island (UHI) effect significantly impact global and urban temperatures, leading to more frequent and intense extreme heat events and dangerously hot days worldwide (Keith et al., 2019). Between 1980 and 2020, heatwaves, which are extended periods of extreme heat, accounted for 86% to 91% of all deaths linked to weather- and climate-related extreme events in the countries of the European Environment Agency (EEA, 2024) and were responsible for more deaths annually globally than hurricanes, lightning, tornadoes, floods, and earthquakes combined (Luber et al., 2008). These extreme heat events also present health, social, environmental, energy, and economic risks (Meteorological Organization, 2023a; Zuo et al., 2015), especially for vulnerable groups such as children, the elderly, low-income households (Keith et al., 2019), and those who are socially disadvantaged, have chronic or mental health conditions (Zuo et al., 2015). Given that the duration, intensity, and frequency of heat events are likely to increase, factors like an ageing population and growing urbanization will make people even more vulnerable to such extremes.

In Europe, people spend 90% of their time indoors (European Commission, 2003), making it crucial to maintain safe and comfortable indoor environments. Currently, buildings are responsible for about 40% of the EU's total energy consumption and 36% of its energy-related greenhouse gas emissions. These emissions mainly come from heating, cooling, hot water, cooking, lighting, and appliances, as reported by the IEA & UNEP (2018) and the European Commission (2020). As of 2020, approximately 85% of the European building stock was constructed before 2001, and it is expected that these structures will still be in use by 2050. Notably, 75% of these buildings are often inefficient and not adapted to the changing climate, like extreme heat events (European Commission, 2020). Additionally, according to the statistics of Eurostat (2024), the average number of heating degree days, defined as the difference between the average daily temperature at a given location and 18°C, stands at around 3200 per year. In contrast, the number for cooling degree days is 78. This explains why most buildings constructed earlier were primarily equipped with heating systems. However, the data also indicate that the demand for heating in 2022 was approximately 15% lower than in 1979, while the demand for cooling has almost quadrupled. This research was further supported by a study by Gassert et al. (2021), which confirmed the rising cooling demand in the Netherlands and predicted that this trend will continue to increase over the coming decades.

Currently, one in three households in the Netherlands cannot adequately cool their homes during warm days (CBS, 2024). Therefore, combined with the results for the need for cooling, as indicated by the data on cooling degree days, and the urgency to protect people from extreme heat events while minimizing energy use and greenhouse gas emissions, is increasingly pressing (European Commission, 2020). At this moment, only 1% of buildings in the EU undergo energy-efficient renovations each year, and these are primarily focused on sustainable heating solutions for residential properties. In addition, in the Netherlands some cooling strategies cannot be assessed according to the BENG standard, and even if they were able to influence the cooling in a building, the method would not be recognised by the standards and would not meet the requirements. Meeting the growing demand for cooling this will lead to a significant increase in the purchase of AC systems, and it is predicted that 40% of homeowners will own an AC system by 2030 (TNO, 2024). These AC systems not only lead to higher energy consumption, but can also use refrigerants that are potent greenhouse gases and directly heat the outdoor environment while cooling the inside (DW Planet A, 2023). In addition, the peak energy consumption of ACs (and solar generation) during an extreme heat event can lead to grid congestion, which increases the risk of power outages (Zuo et al., 2015).

Although numerous studies have recommended passive and low-energy solutions for cooling residential spaces without increasing energy demand, such as the cooling ladder proposed by Duurzaamgebouw (2022), and improvements outlined in a CBE Berkeley guide that highlights the use of fans in combination with HVAC systems for cooling (Raftery et al., 2023), the adoption of these low-energy and passive strategies is not as widespread as it could be. Therefore, this paper will explore this phenomenon in greater detail and provide an answer to the following question: How effective are passive and low-energy cooling strategies in providing heat resilience in existing residential buildings in the Netherlands in a user-centered and resource-efficient manner?

1.2 Problem Statement

The main problem of this research can be stated as:

There is an increasing reliance on air conditioning in response to rising temperatures, despite the availability of effective passive and low-energy cooling strategies that could reduce energy consumption and greenhouse gas emissions in Dutch residential buildings.

This main problem results from several sub-problems that are described below:

- **Impact on Health:** The increasing intensity, duration, and frequency of heat waves pose significant health and safety risks, particularly for vulnerable populations including the elderly, children, low-income groups and those who are socially disadvantaged, have chronic or mental health conditions.

- **Outdated Building Infrastructure:** The majority of European buildings are constructed before 2001 and lack the necessary adaptations for cooling, relying instead on heating systems designed for colder climates.

- **Inefficient Cooling Practices:** Slow renovation rates and outdated cooling practices lead to a dependence on conventional air conditioning units, which are energy-intensive and exacerbate greenhouse gas emissions and grid congestion.

- **Building Standards Compliance:** Current building standards do not incorporate all potential passive or low-energy solutions into the tools for compliance. Therefore, integrating such strategies is not assessed by such standards, making it appear as though they do not meet the building's cooling needs. As a result, standard strategies like HVAC systems are often implemented because their performance can be assessed.

1.3 Objective

- Research Objective

The goal of this study is to evaluate the effectiveness of passive and low-energy cooling strategies in existing residential buildings in the Netherlands as sustainable alternatives to traditional air conditioning during extreme heat events. This evaluation will adopt a holistic approach by incorporating user perspectives and the results of building performance simulations. In this way, six key factors—energy, aesthetics, costs, feasibility, retrofit potential, and comfort—will be assessed for each cooling strategy. This comprehensive evaluation will allow for the comparison of different strategies with varying characteristics, enabling conclusions to be drawn from a user-centered and resource-efficient standpoint.

- Personal Objective

Experiencing extreme heat without effective cooling solutions is a common and uncomfortable issue. My personal objective is to provide an easy-to-understand solution that any homeowner can apply if necessary. For me, this includes mastering new skills with simulation tools, conducting effective interviews, and gaining real-world experience in an engineering office like Buro Happold.

1.4 Research Questions

To address the problem statement outlined in Section 1.2, the following main question (MQ) has been formulated:

MQ1. How effective are passive and low-energy cooling strategies in providing heat resilience in existing residential buildings in the Netherlands in a user-centred and resource efficient manner?

To answer the main research question the following sub-questions (SQ) have been formulated:

SQ1. What influence do the perspectives of residents and real estate developers have on the adoption of cooling strategies in residential buildings?

SQ2. How effective are passive and low-energy cooling strategies in residential buildings, compared to AC systems, in addressing future climate conditions in terms of energy efficiency and occupant comfort?

SQ3. What measures are required to enhance the adoption of passive and low-energy cooling strategies in existing residential buildings in the Netherlands?

SQ4. What are the limitations of current design methods in providing evidence on the benefits of passive and low-energy cooling strategies?

1.5 Relevance

- Societal relevance

This research is of social significance because it addresses the high mortality and health consequences associated with extreme heat, which directly impacts people's lives, necessitating protection against such severe heat conditions. Traditional cooling methods often lead to significant greenhouse gas emissions, high energy consumption, and considerable costs, thereby exacerbating climate change and underscoring the growing need for more efficient cooling solutions. Given that most buildings in the Netherlands are primarily equipped with heating systems, there is an opportunity to adopt cooling strategies that not only enhance thermal comfort and safety for occupants but also improve energy efficiency and reduce costs.

- Scientific relevance

Currently, the majority of buildings constructed before 2000 are not designed to be resilient against extreme heat, impacting occupant comfort and safety. With rising temperatures due to climate change, AC systems are commonly implemented to provide cooling. Although effective, there is a pressing need within the EU, including the Netherlands, to enhance the energy efficiency of such systems. This research aims to scientifically evaluate alternative cooling strategies, assessing them against current air conditioning systems to determine if they can offer comparable comfort with reduced energy consumption.

1.6 Methodology

This research addresses three types: desk, empirical, and synthesis, shown in Figure 1.1. Initially, desk research involves conducting literature reviews to define the problem statement, establish the state of the art, and develop key performance indicators that form the basis of the following stage. This empirical research includes interviews and building performance simulations to rank various cooling options according to different KPIs. In the synthesis phase, these KPIs are compared to answer the main question: How effective are passive and low-energy cooling strategies in providing heat resilience in existing residential buildings in the Netherlands in a user-centred and resource efficient manner?

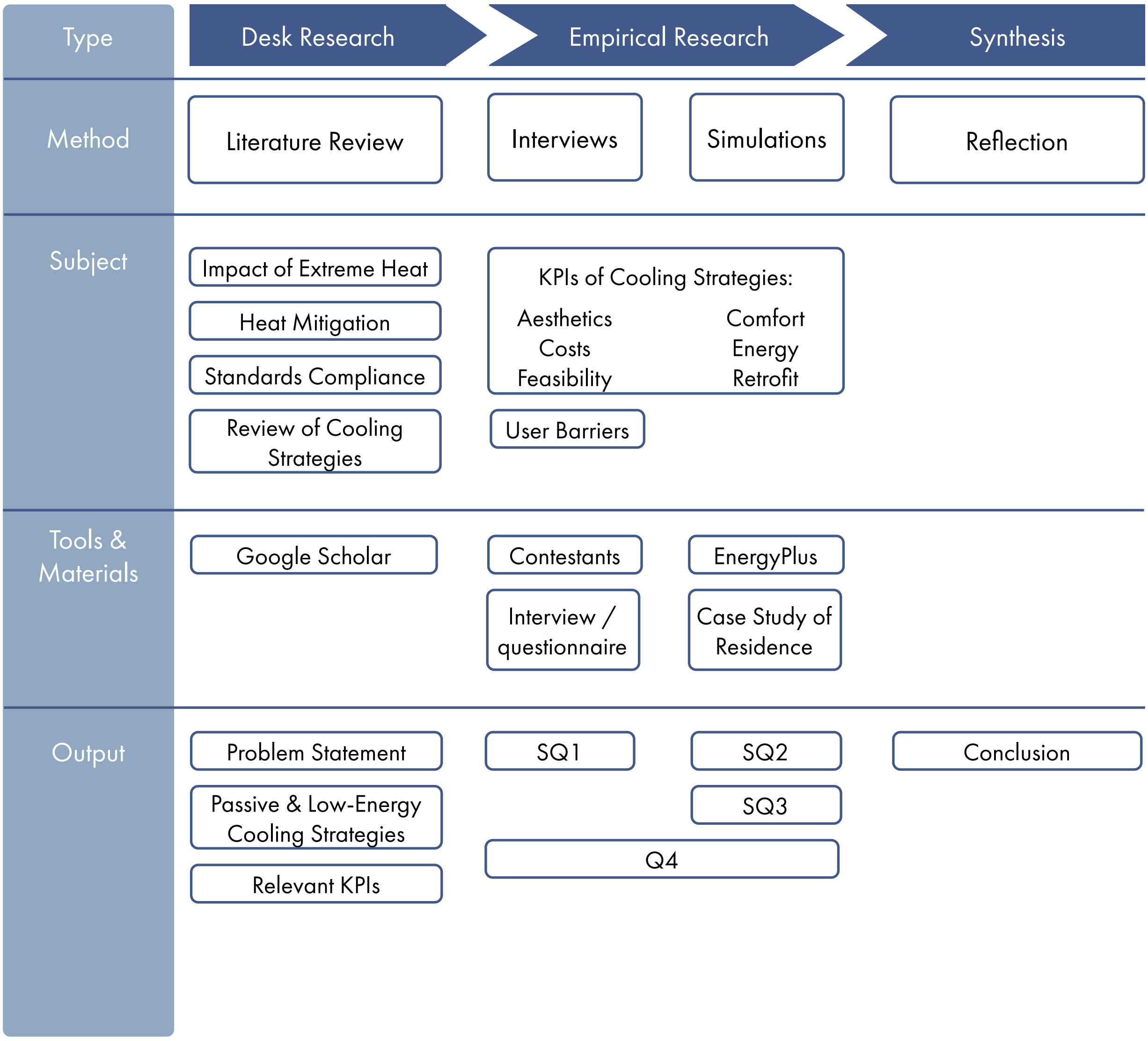

Figure 1.1 - Research Methodology (Own work, 2025)

1.6.1 Desk Research

1.6.1.1. Literature Review

This research began by addressing a significant issue: extreme heat and building resilience. The topic was too broad to explore in a single query for Scopus, so it was divided into several subtopics. Through Google Scholar and ChatGPT, research papers were explored with questions such as the following: What is the impact of extreme heat on human health? How does extreme heat relate to cooling demand? How is the current cooling demand being addressed? What are the consequences of extreme heat and cooling demand? Studies by Zuo et al. (2015) and Keith et al. (2019) provided valuable context for these questions, while data from sources such as Klimaateffectatlas (2024), Eurostat (2024), Gassert et al. (2021), and CBS (2024) offered a clear overview of the current and future status of extreme heat, cooling demand, and strategies to address these challenges.

Initially, the research examined these issues from a European perspective, using resources from Eurostat, the European Commission, and the European Environment Agency (EEA). However, due to the variability in climate, regulations, and needs across Europe, the focus was narrowed to the Netherlands. For this localized scope, resources such as CBS, KNMI, NEN, RVO, and AlleCijfers proved especially useful.

The literature review follows a clear progression from broad to specific. It begins by examining the overall impact of extreme heat, first explaining its effects on human health and comparing future scenarios with the current climate to assess how people might experience such conditions. The review then addresses the connection between rising temperatures and increased cooling demand, introducing the concept of Cooling Degree Days as a measure of the annual cooling required. Given the existing cooling needs, current strategies were explored and evaluated for their potential future relevance. The rapid increase in the use of air conditioning systems stood out, with negative side effects such as higher electricity demand, greenhouse gas emissions, and peak loads being highlighted. The subsequent chapter briefly discusses how extreme heat can be mitigated and the Dutch standards with which such projects must comply. Because only a few passive or low-energy cooling options exist, and large renovations require compliance with BENG standards—standards that do not even account for all possible cooling strategies in their assessment tools (e.g., UNIEC3)—this research focuses solely on retrofitted, low-energy, and passive cooling strategies. These strategies are reviewed in the final section.

Based on the findings from the literature review and discussions with the thesis mentor and engineers from Buro Happold, Key Performance Indicators (KPIs) were established to evaluate each cooling strategy during the empirical research. Figure 1.2 illustrates the different KPIs, with two possible outcomes. The pink line in the center represents the performance of an AC system across these KPIs, while all other cooling strategies are benchmarked against it, shown in blue. In this way, each option can be compared not only to one another but also to AC systems. This is particularly relevant since all strategies have been shown to be effective in research, yet the use of AC systems continues to rise significantly despite their negative side effects. If a cooling strategy outperforms an AC system in all aspects, the resulting diagram could resemble the example in the top right. Conversely, if it performs worse, the outcome would resemble the diagram in the bottom right.

The reasoning behind the selection of each KPI is explained in the following section. It is worth noting that the KPIs may evolve during the empirical research if previously unconsidered relevant issues arise.

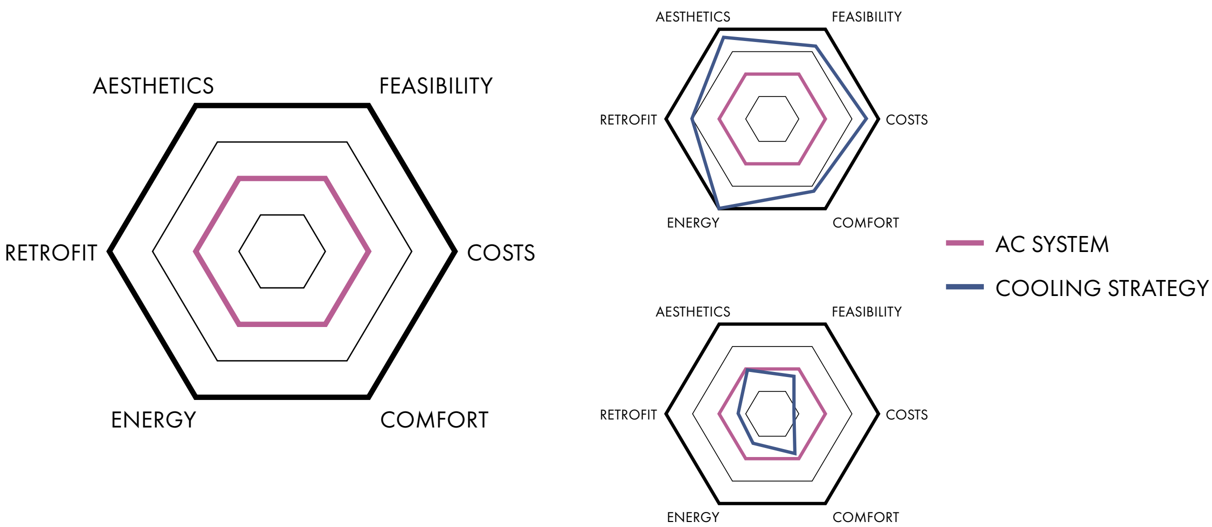

Figure 1.2 - KPIs for Quantifying Effectiveness of Cooling Strategies and Possible Outcomes (Own work, 2025)

- Comfort: The primary goal of any cooling system is to ensure safety and comfort, particularly during extreme heat events. Each strategy is evaluated for its ability to create cooler indoor environments through uncertainty analysis. This approach distinguishes between methods that provide a safe environment with no health-related risks and those that go a step further to achieve optimal thermal comfort. For assessment models like PMV/PPD, TOjuly, and GTO are used, ensuring compliance with Dutch regulations such as the BENG standards.

- Energy: While AC systems are highly effective for cooling, they come with significant drawbacks, such as high energy consumption, which contributes to greenhouse gas emissions and increases the risk of energy grid congestion. This KPI evaluates the potential energy savings of alternative cooling strategies compared to AC systems. For passive methods, energy savings are calculated based on the reduced reliance on AC usage, as these methods do not consume energy themselves. For energy-consuming devices, the KPI considers the energy used by the device minus the energy saved compared to using AC systems alone.

- Costs: Low-income households are particularly vulnerable to extreme heat. Since wealthier households are more likely to have an AC, the investment and operational costs of cooling methods could significantly influence purchasing decisions. To compare cooling strategies with AC systems, both the initial expenses and the operational costs over time are calculated. Only the electricity costs of active methods are considered for operational costs, as these can be accurately determined based on electricity prices and power consumption. Maintenance costs are excluded due to their significant variability.

- Feasibility: Given the slow renovation pace within the EU, this KPI evaluates the time, effort, and expertise required for the installation and operation of the cooling solutions. A higher score indicates that the solution is simpler and faster to implement compared to an AC system.

- Aesthetics: Some cooling strategies can impact the appearance of a building's exterior or interior. This KPI evaluates how satisfied building occupants or real estate developers are with the visual integration of the implemented cooling strategy compared to an AC system, considering aesthetic preferences.

- Retrofit: The low-energy and passive cooling strategies considered in this study focus solely on retrofitting rather than full-scale renovations. While the impact of retrofitting is smaller than that of renovations, the implementation of these strategies may require modifications to the interior or exterior of the building. Additionally, not all strategies are suitable for every type of residential building. This KPI evaluates the specific modifications required for each strategy and assesses their feasibility across different residential building types.

1.6.2. Empirical Research

The empirical research consists of two approaches: interviews and building performance simulations. The purpose of these methods is to gather the necessary Key Performance Indicator (KPI) values for each cooling strategy, providing answers to the four sub-questions of this study. This data will then be analyzed during the synthesis phase, leading to conclusions and identifying potential areas for further research.

1.6.2.1. Interview

Discussions with Buro Happold provided valuable insights into how an engineering firm approaches cooling strategies, ensuring compliance with building standards and addressing client preferences. These discussions highlighted that users have significant influence on the integration of cooling methods, making it essential to consider their perspectives and preferences. The primary user groups to be interviewed are likely residents and real estate developers, as their input is critical to the research.

To ensure both qualitative insights and a sufficient sample size, a questionnaire will be distributed to residents. This approach allows for collecting data from a large number of participants without limiting the study to a specific type of homeowner. In contrast, there are far fewer real estate developers than residents, so qualitative interviews will be conducted with around ten different companies. This will provide a broad range of perspectives and a deeper understanding of the challenges and preferences related to cooling strategies.

These interviews and questionnaires will provide real-life reasons behind design decisions for cooling strategies, complementing technical data found online and during simulations. Additionally, SQ1 could be answered after this phase. Key focus areas derived from the KPIs include:

- Aesthetics: Participants will evaluate various cooling options to determine their perspectives and preferences for these methods in buildings. Additionally, a distinction will be made between strategies integrated during the initial design and construction process and those implemented as retrofits. This approach will help identify aesthetic preferences for each cooling method and allow for a comparison between them. The strategies are not linked to their performance or other KPIs to avoid bias.
- Costs: Real prices for materials, installation, and operating costs in the Netherlands will be researched and compared. Interviews will also be conducted to understand participants' budgets for integrating cooling methods and the types of investments they are willing to make. To ensure objectivity, costs will not be linked to specific cooling strategies, avoiding potential bias in the responses.
- Feasibility: Questions will assess the importance of ease of implementation and operation in choosing cooling methods. This includes understanding the expected expertise required, the frequency of maintenance, and how strategies are activated (if adaptable) during heat events. Facts can be derived from current service companies. To prevent bias, facts are presented independently of the strategy, allowing participants to make their evaluations based on this information.

1.6.2.2. Simulations

Certain KPIs cannot be evaluated through interviews alone. To quantify the effectiveness of energy and comfort, as required for SQ2, building performance simulations will be conducted using EnergyPlus. By inputting data for various types of residential buildings, key factors can be analysed. When the extent and performance of all cooling methods are simulated, it becomes clear what resources and adjustments are required, which can then be linked back to the feasibility, retrofit, and costs KPIs, as required for SQ3. The key focus areas derived from these KPIs are:

- Comfort: To verify the reliability of a cooling strategy, various extreme heat conditions will be simulated in the case study to determine if it meets the safety and thermal comfort requirements outlined in BENG. It is assumed that AC systems, which are commonly purchased due to their perceived reliability, will consistently meet these benchmarks, assuming there is no shortage in electricity supply. However, other strategies may also rely on factors such as weather conditions, which should be taken into account and included in the comparison. Additionally, the combination of multiple strategies may achieve comfort standards more effectively, and this possibility should also be taken into consideration.
- Energy: The optimal configurations for each cooling strategy are simulated to calculate energy savings compared to using only an AC system. If a strategy fails to meet the required safety or comfort benchmarks, the additional energy required to achieve these standards is calculated as if the strategy were supplemented by an AC system. If multiple methods together meet the comfort requirements, they will be combined, and the energy savings will be calculated for the combined approach.
- Retrofit, Feasibility and Costs: When the cooling strategies are implemented to their maximum extent in the simulation program, it becomes clear how much retrofitting is required and the associated investment costs. Additionally, the retrofitting reveals the time and expertise needed for implementation, as well as the energy costs during operation.

1.6.2.3. Comparing KPIs

When all the KPIs are evaluated for the different cooling strategies, including potential combinations, they can be incorporated into the KPI diagram shown in Figure 1.2. Each strategy will first be analysed individually, and if applicable, in combination, to compare their KPI performance against that of an AC system. These diagrams will provide a clear visual representation of all data, highlighting both the improved aspects and limitations of each strategy. This comprehensive analysis will enable the answer to SQ4 to be formulated.

1.6.3. Synthesis

Once all four sub-questions have been answered, a discussion and conclusion can be written. This will include an evaluation of any potential limitations of the research, suggestions for future studies, and a final conclusion providing an answer to the main research question.

1.6.4. Research Limitations

- Applicability Across Residential Types: This research is limited to existing residential buildings, and not all cooling strategies may be applicable to every type of residence. Multiple case studies and simulations will be conducted to ensure a broad applicability of the findings.
- Dependence on External Data: The literature review relies on external data, such as energy consumption and cost values primarily from studies like Oropeza-Perez & Østergaard (2018) focused on Mexican residential buildings. This may not directly translate to the Dutch context due to differences in climate, energy prices, and local purchase costs, potentially affecting the values of the results.
- Thermal Comfort Models: Thermal comfort is assessed using models established by BENG, as they comply with Dutch regulations. However, in Appendix 3.1, alternative models are compared, showing that adaptive models often produce different comfort values compared to static models. Static models rely on assumptions about metabolism, humidity, and clothing, which are not measured in real-life situations and cannot adjust dynamically during calculations.
- Dependency on External Factors: Some strategies depend on external factors such as electricity availability or weather conditions (e.g., wind). Assumptions about these factors are made for the simulations, but actual outcomes may vary in practice.
- Combining Strategies: If a single strategy cannot meet the comfort requirements, combinations of multiple strategies may be necessary. The necessity to combine multiple strategies when a single one fails to meet comfort requirements is based on assumptions and literature insights. Combinations should be considered early in the process, even if not initially seems necessary, based on user preferences and insights gathered during interviews.
- Adaptability of Cooling Strategy: Some cooling strategies are not adaptable. This can lead to a situation where the cooling strategy is designed to reduce the heat gain of the building in summer, but this method also reduces the heat gain in winter. In this way, an effective cooling strategy can lead to a higher heating demand in winter with also the associated energy problems. This therefore requires considering whether to exclude these strategies, exclude the heating demand of winter, or also make simulations of the strategies during winter climate conditions.
- Current Cooling Strategies: The CBS (2024) study indicates an increase in air conditioner usage but lacks detail on the effectiveness of existing cooling methods used. A case study is essential to evaluate the performance and acceptance of current strategies before considering an increase in air conditioning adoption.

1.7 Planning and Organisation

P2 - Formal Assessment - 27/01/25

- Research Framework Setup: Establish the foundation and approach for the research.
- Desk Research - Literature Review
- Interview Set Up

P3 - Compulsory Progress Review

- Draft Empirical Research
- Interview Setup and Execution:
- Questionnaire Setup and Execution
- Initial Simulation in EnergyPlus
- Determine AC System KPIs: Define key performance indicators for the air conditioning systems within the case study.
- The first cooling strategies are implemented in the Case Study Simulation
- Draft Comparison of KPIs: Begin comparative analysis of draft KPIs based on initial simulation results.

P4 - Formal Assessment

- Complete Empirical Research
- Finalize Simulation in EnergyPlus
- Compare KPIs of Cooling Strategies
- Draft Conclusion and Discussion
- Conceptual Thesis Report

P5 - Formal Assessment

- Synthesis of Research
- Final Thesis Report
- Reflection Report
- Render Cooling Strategies in EnergyPlus

2. LITERATURE REVIEW

2.1 Impact of Extreme Heat

It's unavoidable: each year, new temperature records are set, and numerous articles highlight the effects of global warming. Climate change is raising the Earth's average temperature by several degrees. When combined with the Urban Heat Island (UHI) effect, this leads to more frequent and severe extreme heat events and dangerously hot days worldwide (Keith et al., 2019). The impact of extreme heat in the Netherlands on peoples health, the rising demand for cooling, and the subsequent increase in energy consumption, followed by excessive power use, will be explored in the following sections.

2.1.1. Health, experience during future temperatures

The Apparent Temperature Map in Figure 2.1 shows the felt temperature for a tropically warm summer afternoon across the Netherlands, calculated using the Physiological Equivalent Temperature (PET) indicator. PET is influenced by air temperature, wind speed, humidity, direct or reflected sunlight, and environmental heat radiation, which all vary by location due to the design of the built environment (Klimaateffectatlas, 2024).

In the current scenario, as illustrated in Figure 2.1 (left), the apparent temperature reaches up to 43°C in certain areas, described in Figure 2.2 as an extreme heat experience. Additionally, this extreme heat causes heat stress, meaning the body struggles to regulate its temperature. Symptoms can range from mild discomfort to dehydration and severe heat illnesses, potentially resulting in premature death (Klimaateffectatlas, 2024). In such conditions, particularly vulnerable groups such as children, the elderly, low-income households (Keith et al., 2019), and those with chronic or mental health conditions (Zuo et al., 2015), require cooling measures to ensure safety. These temperatures are typical for a tropical summer day, predominantly in southern Netherlands and around large cities, due to the UHI effect. The rest of the Netherlands experiences temperatures around 30°C, which are described as uncomfortable but not leading to severe heat stress. By 2050, as illustrated in Figure 2.1 (right), the situation is expected to worsen, with apparent temperatures starting at 37°C, considered hot and likely to cause significant heat stress. In the southern parts and around big cities, temperatures could rise to 50°C, categorized as extremely hot and leading to extreme heat stress. These predictions highlight the urgent need to create a safe environment during these warm summer days.

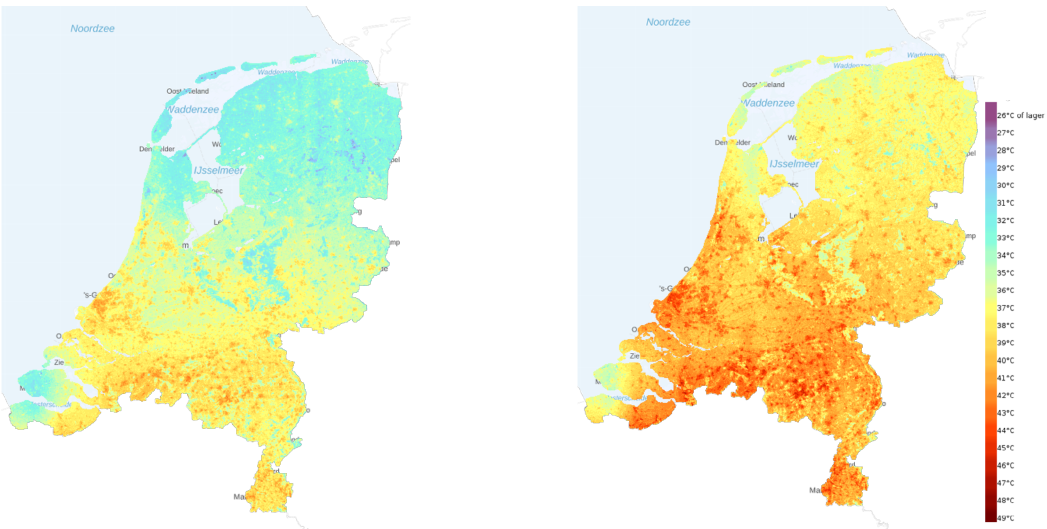

Figure 2.1 - Apparant Temperature on a warm summer in 2024 (left) and in 2050 (right) (Klimaateffectatlas, 2024)

Experience	Comfortable	Minimal	Warm	Hot	Extreme hot
$T_{apparent}$	<23	29	35	41	>41

Figure 2.2 - Apparant Temperature and it's risk level (Klimaateffectatlas, 2024)

2.1.2. Cooling demand, cooling degree days

In Europe, people spend 90% of their time indoors (European Commission, 2003), so to keep them safe from the increasing temperatures outside it is crucial to maintain safe and comfortable indoor environments. Heating and cooling degree days are metrics used to estimate the energy required to heat or cool buildings to comfortable levels based on external temperatures. A "degree day" is counted when the average daily outdoor air temperature deviates by one degree from a standard comfortable baseline of 18°C. The total of heating or cooling degree days over a year approximates the yearly energy needed for temperature regulation in that location. Note that the baseline air temperature only measures the outside temperature of the air where the apparent temperature in the previous Section also considers other factors.

Europe was cooler and more often experienced harsh winters than severe summers. According to the statistics of Eurostat (2024), Figure 2.3, the average number of heating degree days in Europe was 3200 per year (left), while the number for cooling was only 78 (right). This explains why most passive and active methods in buildings have historically been used for heating rather than cooling. However, these statistics also showed that the demand for heating in 2022 was 15% lower than in 1979 and continues to decline, whereas the demand for cooling has instead quadrupled and are still increasing.

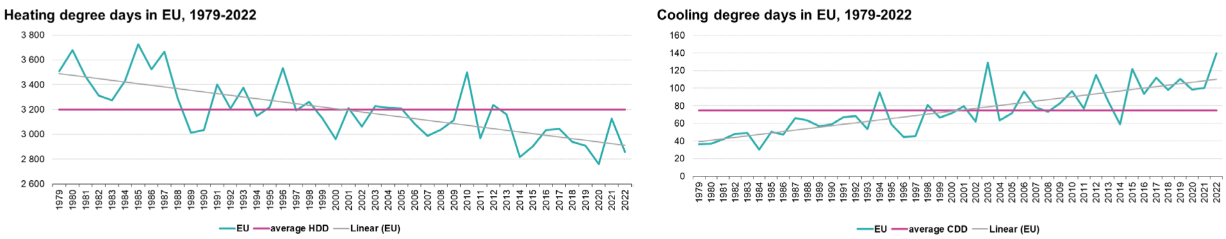

Figure 2.3 - Heating (left) and Cooling (right) Degree Days in EU, 1979-2022 (Eurostat, 2024)

The Change in Cooling Degree Days (CDD), shown in Figure 2.4 illustrates the annual variation in CDDs for 2030, 2050, and 2080 in the Netherlands, compared to a baseline period from 1960-1990 (Gassert et al., 2021). In 2030, the CDDs are expected to range between 25 and 75, which aligns with the European Union average previously discussed. By 2050, a significant increase is primarily noted in the southern parts of the Netherlands, with CDDs expected to range between 500 and 1000, representing an increase of 1400% over 20 years. By 2080, CDDs across the entire country are projected to rise sharply, exceeding 1000, which marks an approximate increase of 2000% from 2030 levels.

Figure 2.4 - Change in Cooling Degree Days in the Netherlands 2030 - 2050 - 2080 (Gassert et al., 2021)

All these figures, comparing apparent temperatures and cooling degree days for the current situation and projections for 2050 and beyond, underscore the potential for temperature increases to create hazardous conditions. This escalation in heat will necessitate cooling in buildings to keep inhabitants safe. Thus, it's crucial to review current cooling methods to determine their effectiveness in the face of rising temperatures and growing cooling demands.

2.1.3. Current cooling strategies

According to statistics from CBS (2024), one in three households in the Netherlands are unable to keep their homes cool during hot days. Given that nearly 95% of the Dutch building stock consists of residential units (Allecijfers, 2024) , this represents a significant number of homes and primarily affects those living in rental properties (both private and social), flats, and older houses. Additionally, lower-income households, who are more likely to live in these rental units and apartments, experience this even more, with nearly half reporting that their homes could not be adequately cooled during warm weather, compared to about a quarter of higher-income households living in owner-occupied homes.

The most common cooling methods in the Netherlands calculated by CBS (2024) include opening windows at night (72%), closing windows and curtains during the day (66% and 62%, respectively), and using solar shading on windows (over 50%). In terms of active cooling measures, 35% of households use fans, and 20% have AC systems. It is noteworthy that 5% of households in rental properties have a fixed air conditioner, compared to 18% in owner-occupied homes. Additionally, within the next two years, 13% of residents in owner-occupied homes without air conditioners plan to purchase one. It is unclear what types of passive and low-energy cooling methods are currently available to these individuals, and whether they have considered these alternatives before opting to buy an air conditioner.

While the adoption of active cooling measures like air conditioners is still relatively low compared to other methods, their purchase has seen a dramatic increase. In 2019, around 231,000 homes had air conditioning, a number that rose to 1.3 million by 2023. According to the Dutch Organization for Applied Scientific Research (TNO, 2024), this trend is expected to continue, with projections suggesting that over 40% of households will have at least one air conditioner by 2030. This surge in air conditioning is set to significantly boost energy consumption and emitted Green House Gasses (GHG) for cooling.

The reason why homeowners are more likely to choose air conditioning systems over low-energy or passive cooling solutions is because they can lower indoor temperatures by more than 15°C, regardless of humidity levels—something fans and similar systems cannot achieve. This makes air conditioners a versatile option suitable for any building, regardless of climate conditions (Oropeza-Perez & Østergaard, 2018). Furthermore, the increased mortality rates associated with extreme heat events have been linked to the lack of air conditioning, which has contributed to their growing popularity (Zuo et al., 2015).

2.1.4. Electricity consumption, peak loads

If the trend of rising air conditioner sales continues, it will have a profound impact on global energy demand. The International Energy Agency (IEA) estimated that in 2022, global consumption for space cooling with air conditioners was about 2,100 TWh, which, compared to the global total electricity use of 29,000 TWh, accounts for nearly 7% of the world's electricity and 20% of electricity use in buildings. Additionally, the high energy use, most electricity is derived from fossil fuels, contributing to an estimated emission of 1 billion tonnes of green house gasses in 2022. Although significant, the energy consumption and green house gas emissions from space and water heating are still four times higher, even as they are on the decline (Ritchie, 2024).

The increase in the number of air conditioners and the associated electricity consumption introduces an additional issue: peak demand (Zuo et al., 2015). Peak demand occurs when the demand for, or supply of, electricity exceeds the capacity of the grid to transport it simultaneously. During extreme heat, the widespread use of air conditioners for cooling, combined with high solar energy generation for example, can lead to grid congestion. This congestion increases the risk of power outages.

For this reason, governments are encouraging measures to reduce and redistribute energy consumption throughout the day. Since there is a direct demand for cooling during extreme heat, it is essential to promote cooling methods that are either independent of the power grid (passive) or require minimal electricity.

2.2 Heat Mitigation

2.2.1. Basic principles, heat transfer

When studying the overheating of a building and effective cooling methods, it's beneficial to understand the basic principles of heat transfer. There are variables that influence the heat load caused by the external environment compared to the indoor conditions. This understanding is essential because the heat lost by one side of the building is essentially balanced by the heat gained on the other side, adhering to the principles of energy conservation in thermodynamics. Heat can be transferred in three ways, as illustrated in Figure 2.5 (Alfa Laval, n.d.): 1) Radiation, where energy is transferred through electromagnetic radiation such as solar irradiation heating up a building. 2) Conduction, where energy is transferred between solids or gases through the movement of atoms and molecules. This can be likened to transmission through a building where heat transfers through the roof or facade. 3) Convection, where the energy of a medium is mixed with a part of another medium. This can be compared to the ventilation of a building where indoor and outdoor air is mixed, and heat is transferred within that.

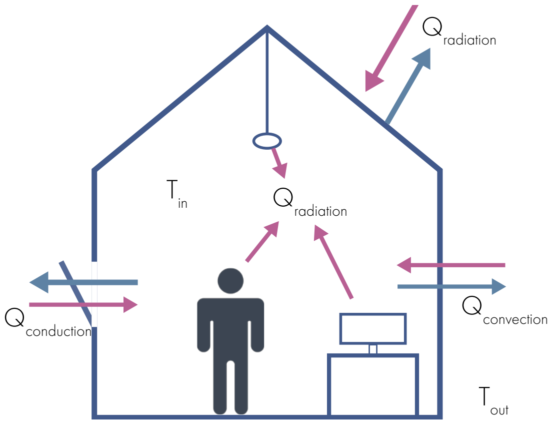

Figure 2.5 - Heat Tranfer of a Building (Own Work, 2025)

Heat Load = m * c * ΔT [kW]
Heat Transfer = h * A * ΔT [W]

m = Mass Flow of Medium [kg/s]
c = Specific Heat Capacity [kJ/kg·°C]
A = Heat Transfer Surface [m^2]
h = Heat Transfer Coefficient [W/(m^2K)]
ΔT = Temperature Difference = T_{out} - T_{in} [°C]

2.2.2. Optional Cooling Strategies

When a building absorbs more heat than it can dissipate, it heats up. If this heat load surpasses comfortable levels, the building needs cooling to maintain a healthy indoor environment and to provide safety during extreme heat events. The Cooling Ladder, part of the "Climate Change and Building Cooling" declaration of intent by OSKA, highlights the importance of evaluating different cooling strategies based on their desirability and effectiveness, as depicted in Figure 2.6 (Duurzaamgebouw, 2022).

1) Environmental Cooling: This step focuses on directly reducing the external temperature around buildings. By integrating trees, green façades, green roofs, and utilizing water features the overall outdoor temperature can be lowered, also mitigating the Urban Heat Island effect. A cooler external environment results in less heat being transferred indoors, leading to natural cooling.

2) Heat Resistance: Architectural design plays a crucial role in resisting heat. Strategic building orientation and layout, optimizing the window-to-wall ratio, can maximize beneficial solar gains in winter while minimizing them in summer. Additional passive measures, like solar shading devices, overhangs, thermal insulation, and high-reflectivity glass, help prevent heat from penetrating the building envelope.

3) Passive Cooling: These strategies involve design choices that inherently reduce heat gain and promote cooling without additional or with minimal energy consumption. Effective use of natural ventilation through techniques like cross- and night-time ventilation, increasing thermal mass, and seasonal energy storage solutions, such as Aquifer Thermal Energy Storage (ATES), are key methods. These solutions leverage the building's design and materials to maintain comfortable temperatures naturally.

4) Active Cooling: While the previous measures do not consume energy during cooling, active cooling systems do. These options can range from technical solutions like heat pumps and air conditioning systems, which are often complex and consume a lot of energy, to simpler, low-energy devices such as fans.

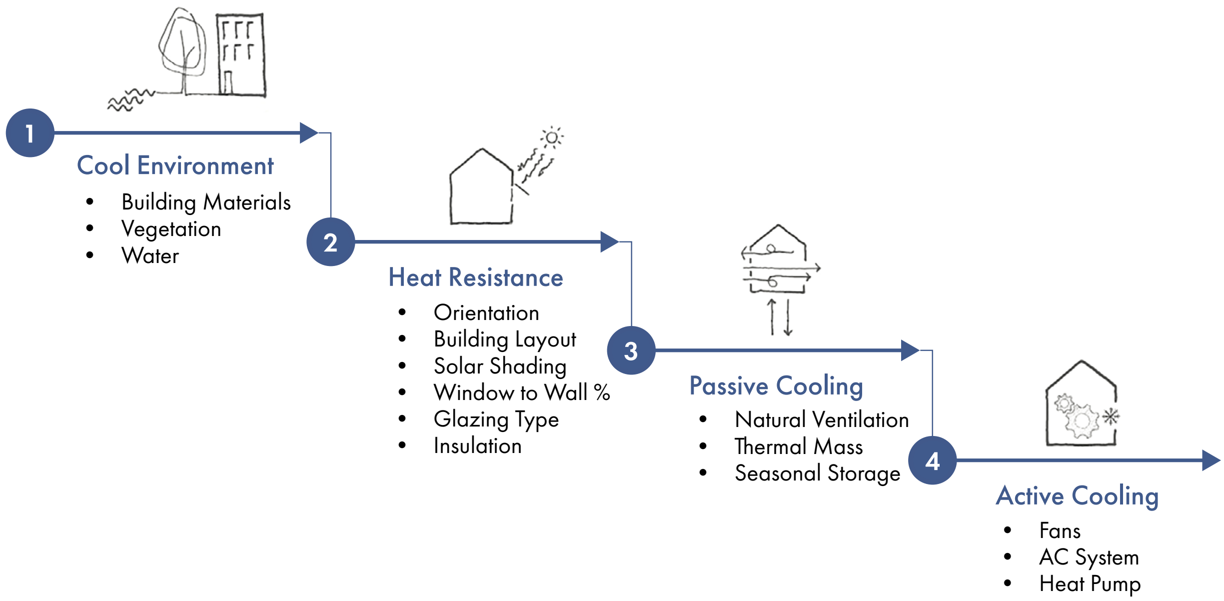

Figure 2.6 - Cooling Ladder derived from Duurzaamgebouw (2022) (Own Work, 2025)

2.3 Standards Compliance

2.3.1. Building Requirements in the Netherlands

When introducing new cooling strategies for buildings, it is crucial to ensure compliance with the regulations in place in the Netherlands. For newly constructed buildings or major renovations, the BENG standard is applied. This standard, aligned with the European Energy Performance of Buildings Directive (EPBD), evaluates buildings based on three key indicators: maximum energy demand, maximum fossil fuel energy consumption, and minimum share of renewable energy (NEN, 2021). Additionally, small building renovations and retrofits are subject to specific legal requirements that set minimum standards, ensuring these projects also meet energy efficiency and environmental objectives.

To determine whether a new building meets the BENG requirements, the technical standard NTA 8800 is used. Software such as Team UNIEC 3 and VABI is employed at Buro Happold to assess compliance. Cooling options like natural ventilation (excluding specific cross or night-time ventilation), solar shading, and air conditioning systems can be included in these calculations. However, radiant heat barriers and fans, despite their practical cooling effectiveness, are not recognized in the assessment, which could lead to the building failing to meet BENG standards. Therefore, this research focuses on retrofitted and small-scale cooling strategies that align with existing building regulations, ensuring impactful methods can be implemented without conflicting with compliance standards.

Although retrofitting does not need to comply with BENG standards, the methods used to calculate thermal comfort are still valuable. Three different approaches can be used to assess the level of thermal comfort experienced by occupants within a building during extreme heat, explained in Section 2.3.2.

2.3.2. Thermal comfort assessment

- **PMV and PPD**

This thermal comfort model from Fanger indicates the percentage of building users who are dissatisfied with the quality of the thermal indoor environment (= Predicted Percentage of Dissatisfied, or PPD). This PPD is derived from the PMV (= Predicted Mean Vote), which measures how the average user assesses the thermal indoor environment. The models are static where is assumed that the environmental conditions and the occupants activity level as clothing remain constant over the time the calculation is made. The factors that influence the calculations are (RVO, 2018):

- Air Temperature (T_{air})
- Mean Radiant Temperature (MRT)
- Air Velocity (v_{air})
- Relative Humidity (RH)
- Metabolic Rate (M)
- Clothing Insulation (I_{clo})

The PMV is expressed as a number that ranges between -3.0 (cold) and +3.0 (hot). At a PMV of 0.0 (= neutral, neither too warm nor too cool), users are generally most satisfied with the thermal comfort in a space. The requirement for 'comfort' usually specifies that the PMV in a space should only exceed the range of -0.5 to +0.5 for a certain number of hours. For PPD accounts a maximum of 10% dissatisfied to consider the space comfortable. In Figure 2.7 is shown how the PMV and PPD are related to each other.

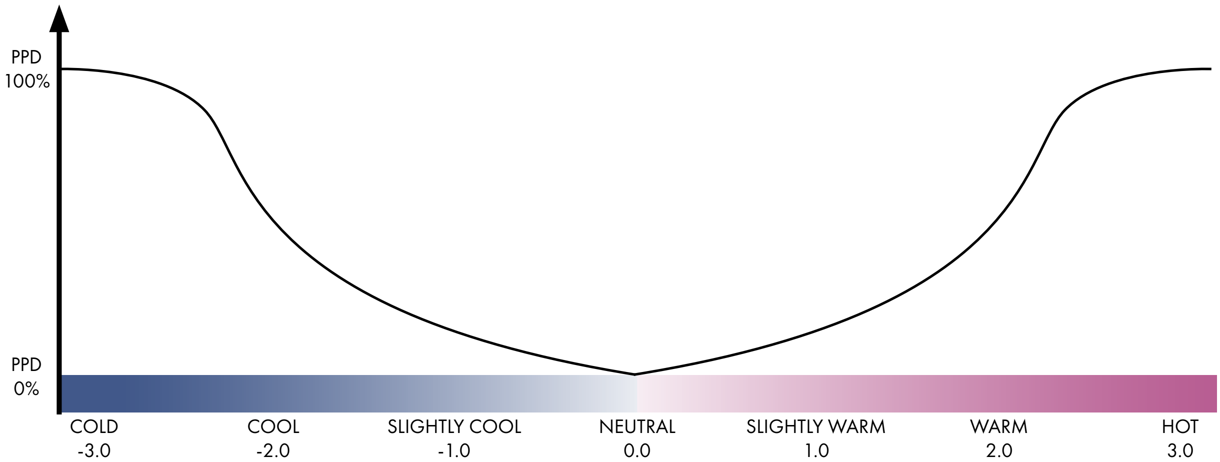

Figure 2.7 - PMV & PPD Levels, derived from RVO (2018) (Own Work, 2025)

Because this model is static, it assumes constant conditions for evaluating thermal comfort during summer using the PMV/PPD indices:

- Air Temperature = Mean Radiant Temperature
- Air Velocity = 0.1 m / s
- Relative Humidity = 50 %
- Metabolic Rate = 1.2 (standing / sitting)
- Clothing Insulation = 0.5 (summer clothing)

The comfortable range (0.5 < PMV < 0.5) with these set factors is between 24.3°C and 27.2°C, with an optimum (PMV=0.0) at 25.7°C. It is important to note that both the metabolic rate and clothing insulation can vary based on individual differences and should be adjusted in the model according to specific occupant characteristics.

In Figure 2.8, the PMV and PPD ranges are presented with corresponding temperatures based on static calculations. Comfort Class A indicates a very comfortable indoor environment with high thermal comfort, whereas Comfort Class C exceeds the maximum comfort range. The online tool from CBE-Berkeley allows for the assessment of thermal comfort according to the PMV / PPD method by inputting various factors.

Comfort Class	PPD	PMV	Operative Temperature
A	< 6%	-0.2 < PMV < +0.2	23.5 - 25.5 °C
B	< 10%	-0.5 < PMV < +0.5	23 - 26 °C
C	< 15%	-0.7 < PMV < +0.7	22 - 27 °C

Figure 2.8 - PMV & PPD Comfort Classes derived from RVO (2018)

- GTO-hours

GTO, or Weighted Temperature Exceedance Hours, refines the standard TO method by not only counting the hours a temperature threshold is exceeded but also considering the severity of the exceedance (RVO, 2018). For example, a temperature of 30°C has a higher weighting than 26°C due to increased discomfort or risk. The GTO method multiplies the number of hours a specific PMV level is exceeded by a weighting factor, reflecting the extent of dissatisfaction as indicated by the PPD model. Unlike the TO-hours method, which uses a fixed temperature value, GTO incorporates PMV's six influencing factors, creating a more nuanced assessment of thermal comfort. This results in a calculation where, for instance, an hour with 10% dissatisfaction is equated to half an hour with 20% dissatisfaction, providing a more accurate reflection of actual discomfort experienced. A preliminary target value is a maximum of 450 GTO-hours per year in a residential building.

- TO_{july}

The TO_{july} number is an indicator that provides insight into the risk of temperature exceedance for each orientation of the building. It is calculated for each calculation zone within a building, and for each orientation of that zone (RVO, 2018). In the calculation of the TO_{july} number, the cooling need is related to the heat losses through convection and conduction (transmission and ventilation). In Figure 2.9, the results of the TO_{july} number, calculated using the formula provided, are shown along with the corresponding risk of overheating associated with each value.

$$TO_{july} = Q_{cooling\_demand\_orientation} / (H_{transmission} + H_{ventialiont}) * t_{july})$$

TO_{july} number	Risk of overheating
0 - 2	No Risk
2 - 4	Medium to High Risk
> 4	High Risk

Figure 2.9 - TO_{July} number with the Risk of Overheating derived from RVO (2018)

Although these models comply with building standards such as BENG and are in accordance with NTA8800, they are not the only methods for assessing thermal comfort. In Appendix 3.1, various thermal comfort models and heat stress models are compared, highlighting their unique characteristics. While more adaptive models can calculate thermal comfort effectively, for use with simulation programs, the more static factors and assumptions that can be made will prove to be more advantageous.

2.4 Review of Cooling Strategies

As previously mentioned, most of the Dutch building stock consists of residential units. Despite efforts by the European Union and the Dutch government to promote sustainable renovations that make buildings more resilient to extreme heat events, only 1% of buildings in the EU undergo energy-efficient renovations each year, which are often focused solely on sustainable heating solutions (European Commission, 2020). This is compounded by the fact that major renovations must comply with BENG standards, which do not include all strategies in their assessment tools. Therefore, this research focuses exclusively on cooling solutions that can be implemented through retrofitting. Additionally, only strategies that provide immediate cooling upon use are considered. For instance, planting a tree to create shade requires a long time to take effect and therefore does not meet the criteria for immediate impact. Below is a review of possible active and passive solutions from the cooling ladder. In Figure 2.10, all characteristics are compared based on the study by Oropeza-Perez & Østergaard (2018).

- Fans

A fan, also known as an air movement device, is an electrical appliance powered by a motor that rotates three or four blades at a constant speed. This rotation creates pressure differences around the blades, producing airflow. The generated airflow cools surfaces through forced convection and transfers heat while cooling people via evapotranspiration. In this process, heat is exchanged between the moving air and the sweat on human skin, causing the sweat to evaporate from liquid to gas, which absorbs and removes heat. This mechanism allows the body to maintain thermal comfort at higher air temperatures than would be tolerable in still air. However, the cooling effect only occurs while the fan is running and does not persist after it is turned off.

There are various types of fans, including ceiling fans, pedestal fans, desk fans, and tower fans. These differ in size, design, spinning speed, placement, function, application, required space, noise levels, and energy consumption (Raftery et al., 2023). For example, desk fans are smaller and designed to direct airflow towards the human body for more effective evapotranspiration. In contrast, ceiling fans are larger, require more significant retrofitting, take up more space, and provide air circulation for the entire room.

Energy consumption for fans varies depending on the type and features, typically ranging from 50 to 185 watts to move up to 220 m^3 of air per hour across an area of about 120 m^2. Using fans in this manner can achieve the feeling of a temperature reduction of up to 6°C. In terms of cost, a basic fan can be purchased for as little as €20, while models with more advanced functionalities may cost upwards of €150, depending on aesthetic preferences and budget constraints.

- AC System

An air conditioner operates using a common cooling system. A refrigerant in gas form is compressed, increasing its pressure and temperature, turning it into superheated vapor. This vapor flows through a condenser, where it is cooled with air or water, causing it to condense into a liquid as excess heat is removed. The liquid refrigerant then passes through an expansion valve, undergoing a sudden pressure drop that partially converts it back to gas, creating a cold mixture. This mixture moves through an evaporator, cooling the warm indoor air. The cycle repeats as the refrigerant returns to the compressor. The cooling effect of an air conditioner comes from its ability to lower air temperature, easily controlled to reduce it by more than 15°C regardless of humidity.

There are two types of air conditioners: fixed and portable. Fixed systems, the most common, are installed on walls or ceilings, with piping integrated into the structure to connect the indoor unit to the outdoor unit, requiring significant retrofitting. Portable ACs, on the other hand, are movable and can be placed anywhere, though they should be positioned near a window to vent warm air effectively. While portable systems require minimal space, fixed systems often demand additional room for piping and the outdoor unit.

To cool an area of 120 m^2, an AC typically uses 800 to 4000 watts per hour and around 6000 watts to lower the temperature by 10°C. Once the room is cooled, a fixed AC consumes relatively little energy, averaging 0.75 kWh per hour. The purchase price of an AC starts at approximately €800 and can rise to several thousand euros, excluding operational energy costs.

- Natural Ventilation

Natural ventilation, as defined by ASHRAE, is the introduction of outdoor air into a building driven by naturally occurring pressure differences. It relies on two primary forces: buoyancy and wind pressure. Buoyancy, also known as the stack effect, occurs when variations in air temperature create differences in air density between the indoor and outdoor environments. Warmer air, being less dense, rises, generating upward airflow within enclosed spaces. Wind pressure impacts ventilation when wind strikes a building, creating pressure differences across its exterior. The side of the building facing the wind experiences higher pressure, while the leeward side has lower pressure. These pressure differences drive air movement through the building, creating natural airflow. Natural ventilation is a valuable cooling method, achieved through three main mechanisms: cooling the indoor air when outdoor temperatures are lower, reducing heat stored in the building structure through convection, and cooling the human body directly via evapotranspiration. The effectiveness of natural ventilation in lowering indoor temperatures depends on external factors such as outdoor temperature and wind speed. Under favourable conditions, it can reduce indoor temperatures by 4 to 15 °C. However, its impact and controllability can vary significantly.

There are two types of natural ventilation considered: Cross ventilation and night-time ventilation. Cross ventilation involves strategically opening windows, vents, and doors to allow air to flow into and out of the building naturally. This method uses air movement to create a cooler and more comfortable indoor environment. Night-time ventilation, on the other hand, cools the building structure itself by releasing heat through convective transfer during unoccupied hours. During the day, the building absorbs heat from internal and external sources, acting as a heat sink. At night, these accumulated heat gains are then released and expelled from the building through natural ventilation. This cooling process during the night ensures that the building maintains comfortable temperatures for occupants the following day. Although night ventilation has proven to be effective, its potential is greater when there are no internal heat gains from occupants and lighting at night, making it less suitable for residential buildings.

- Radiant Heat Barriers

Radiant heat barriers are materials installed on the exterior facade of a building's envelope, designed to reflect radiant heat and prevent it from penetrating the structure, similar to the second step of the cooling ladder. Reflectivity is measured on a scale from 0 to 1, with 0 representing no reflection (like a black box) and 1 indicating total reflection (like pure white) across the visible light spectrum. Studies and practical experience demonstrate that lighter colors are more effective at reflecting radiation than darker ones, making them preferable for reducing heat absorption in buildings. Radiant heat barriers can lower indoor temperatures by up to 13°C without requiring additional energy. However, this measure is not adaptable during heat events and also reduces heat absorption in winter when additional heat gains are desirable. Additionally, a dwelling may be situated between multiple floors and other homes, meaning that a roof-based cooling strategy does not directly impact units that are not located directly beneath the roof.

There are various types of radiant heat barriers for roofs, each reducing heat gain differently. Naturally cool roofs, often made of white vinyl or polyvinyl chloride (PVC), are inherently reflective, reflecting up to 80% of sunlight. Another option is coating roofs with light-colored paints to enhance reflectivity. Green roofs take a different approach, covering the roof with vegetation like grass and bushes. These roofs not only reflect 30-50% of sunlight but also serve as convective barriers and provide cooling through evaporation and conductive insulation. This makes them a multifunctional solution for improving energy efficiency and reducing heat in buildings.

The cost of installing a radiant heat barrier for a 120 m^2 dwelling ranges from €30 to €9,600, depending on the type of barrier and roof size. Applying a reflective coating involves less retrofitting compared to installing a green roof, although both require expertise and safety considerations. Additionally, the challenges and aesthetic preferences for modifying flat roofs differ significantly from those for sloped roofs.

- Solar Shading

Solar shading serves the same purpose as radiant heat barriers by preventing solar radiation from penetrating the building's envelope, particularly through windows. The shading has to be on the outside of the building otherwise the heat will accumulate in between the shading and the window inside of the building. It can achieve a maximum temperature reduction of 3°C, thus creating a cooler indoor environment.

Other methods to control solar heat gain include adjusting the building's orientation, altering its shape and creating overhangs or eaves. Among these options, solar shading is the most suitable for retrofitting, as it requires minimal space and does not involve extensive renovations. For this reason, solar shading is the preferred solution for existing residential buildings. The costs depend on aesthetic preferences and budget, starting at as little as €20 to cool a 120 m^2 home.

	Power [W]	Max. ΔT [°C]	Cost [€]	Retrofit	Required Space	Extra
Fans	50-185	~ 6	20-250	Low - High	Low	• Noise • Increased Ariflow
AC	800-4000	> 15	400-2200	High	Medium	• Noise • In- & Outside Unit • Maintenance
Natural Ventilation	0	~ 13	0-1000	Low	Low	• Weather Depended
Radiant Heat Barriers	0	~13	30-9600	Medium - High	Low	• Not Adaptable • Less Heat Gain during Winter • Maintenance
Solar Shading	0	~ 3	20-500	Medium	Low	• Blocks View & Natural Lightning • Influence on Appearance

Figure 2.10 - Comparison between Active and Passive Retrofit Cooling Strategies

In Appendix 3.2, the formulas and methods for determining the effectiveness of each cooling strategy are provided.

3. APPENDIX

	PMV/PPD	To	WBGT	SET*	HI	PHS	Two-Node	TO_{July}	GTO	ATG
Full name	Predicted Mean Vote/ Predicted Percentage of Dissatisfied	Operative Temperature = Adaptive	Wet Bulb Globe Temperature	Standard Effective Temperature	(Psychrometry) Heat Index	Predicted Heat Strain	Two-Node Model of Human Thermoregulation	Temperatuur Overschrijding = Temperature Exceedance	Gewogen Temperatuur Overschrijding = Weighted Temperature Exceedance	Adaptieve Temperatuur Grenswaarde = Adaptive Temperature Threshold
Model Type	Thermal Comfort Model	Thermal Comfort Model	Heat Stress Model	Heat Stress Model	Heat Stress Model	Heat Stress Model	Thermoregulation Model	Thermal Comfort Model	Thermal Comfort Model	Thermal Comfort Model
Conditions	Indoor, (mechanical-) controlled	Indoor, Naturally ventilated	Indoor, Outdoor workspaces	Indoor, controlled	Indoor, outdoor	Extreme Heat, Occupational	Indoor, outdoor	Indoor, residentials	Indoor, residentials	Indoor
Input	• Air Temperature • Mean Radiant Temperature • Air Velocity • Relative Humidity • Metabolic Rate • Clothing Insulation	• Outdoor Air Temperature (prevailing mean) • Indoor Operative Temperature	• Temperature • Humidity • Wind speed • Solar radiation (Sun angle & Cloud cover)	• Air Temperature • Mean Radiant Temperature • Air Velocity • Relative Humidity • Metabolic Rate • Clothing Insulation	• Air Temperature • Relative Humidity	• Air Temperature • Mean Radiant Temperature • Air Velocity • Relative Humidity • Metabolic Rate • Clothing Insulation	• Air Temperature • Mean Radiant Temperature • Air Velocity • Relative Humidity • Metabolic Rate • Clothing Insulation	• Air Temperature	• Air Temperature • Mean Radiant Temperature • Air Velocity • Relative Humidity • Metabolic Rate • Clothing Insulation	• (Average) Outdoor Air Temperature • (Set) Indoor Air Temperature
Output	• PMV: -3 to +3 • PPD: 0-100%	• Acceptable Comfort Temperature Range (°C)	• WBTG index (°C/°F)	• Standard Effective Temperature (°C/°F)	• Apparent temperature = feels-like temperature (°C/°F)	• Maximum sweat rate • Core temperature increase • Skin wetness percentage	• Core Temperature • Skin Temperature • Thermal Comfort Vote • Sweat Rate	• Number of Hours that the Room Temperature exceeds a certain Temperature Threshold	• Weighted exceedances of comfort levels	• Number of Hours during which the Indoor Temperature exceeds a certain Threshold. • ATG classes (A,B,C) • Percentage of Acceptability
Comfort/Safety Indicators	• Thermal Comfort climate • PMV = 0 = Thermal neutrality • -0.5 < PMV > +0.5 • PPD < 10% • +/-0.2 (Class A), +/-0.5 (Class B), and +/-0.7 (Class C)	• Thermal Comfort Climate • Adaptive	• Safe indoor climate • With overnight occupancy: <28 C° • Without overnight occupancy: <31C°	• Safe indoor climate • Not exceed 5°C SET*-days above 30°C for residentials (120°C SET*-hours) • Not exceed 10 °C SET*-days above 30°C for non-residentials	• Severity of heat stress risk • Safe indoor climate • General risks < 32.2°C • Hospitals < 27°C • Commercial < 39,4°C	• Safe indoor climate • MSR < 1.2 kg/h & < 7.5% of bodyweight • CTI < 38°C	• Thermal Sensation • Heat stress/ strain	• E.g. TO at 25 °C for max. 100 hours	• GTO measured at PMV>0,5	• Class A: highest level (90%) • Class B: good level (80%) • Class C: minimum acceptable level of thermal comfort (65%)
Assumptions	• Steady-state conditions • Uniform clothing • Uniform activity levels	Adjustments to: • Clothing • Activity	Calculation of heat strain	Accounts for convection, evaporation, and radiation • RH: 50% • Air speed: 0.1 m/s • MRT = Air temperature	Calculation of heat strain	Calculation of heat strain	• Steady-state conditions • Uniform clothing • Uniform activity levels	• Threshold must be stated • An exceedance hour occurs when the temperature threshold is exceeded for one hour.		Guidelines depending on: • Alpha Building: lot of occupant influence on indoor environment • Beta Building: controlled indoor environment
User Adaptability	Low; no occupants adjustment	High; considers occupant behaviour: behavioural, physiological, and psychological	Low	Moderate	Low	Moderate; considers acclimatization	Low	Moderate; possibly adjusted by MET and CLO values	Moderate; possibly adjusted by MET and CLO values	Low & High; Alpha / Beta Building
Energy	High; HVAC optimization	Low; reduces reliance on HVAC systems	x	Moderate HVAC optimization	x	x	Low	x	x	Low & High; Alpha / Beta Building
Codes	ASHRAE 55, ISO 7730	ASHRAE 55, EN-15251, NEN-EN-ISO 15251	ASHRAE 55, ISO 7243	ASHRAE 55	NOAA Heat Index standards	ISO 7933		BENG	BENG	ISSO 32, BENG
Certifi-cations	BREEAM	HQM, DGNB, WELL	LEED, RELI	LEED, RELI	LEED, RELI					

Appendix 3.1: Comparison between Thermal Comfort Models and Heat Stress Models (Cui et al., 2023; RVO,2018)

3.2. Formulas of Cooling Strategies

To determine whether cooling strategies have been effective, one can naturally measure how much the temperature has decreased since the implementation of the measures. In this research, it is also interesting to explore how each method leads to cooling. Below are the possible strategies along with potential measurement methods outlined.

General Measurement

- Thermal Comfort: A common method to assess the effectiveness of cooling strategies is to measure the thermal comfort experienced by building users. In Chapter 2.3.2, commonly used thermal comfort models in the Netherlands are further explained.

Heat Resistance

- Solar Heat Gain: Calculate the amount of solar radiation entering the building through windows and facades, and compare this with the heat gain after implementing solar blocking measures such as overhangs, double glazing (with films), shading, or trees.
- EnergyPlus: Software like EnergyPlus can specifically analyze the amount of solar irradiation on a building's surface over a period of time. Only weather data, along with the orientation and dimensions of the building, are required to perform this analysis.

Passive Cooling

- Airflow Rate: Airflow is the measurement of how much air moves through a particular area over a period of time like during natural ventilation. It is quantified either as a volumetric flow rate, which is the volume of air moving per unit of time, or as a mass flow rate, which is the mass of air moving per unit of time.
- Thermal Mass: Thermal mass refers to the ability of building materials to absorb, store, and later release significant amounts of heat. Calculating it requires the density, specific heat capacity and thermal conductivity. Specific heat capacity determines the energy needed to change material temperature by one degree Celsius, while thermal conductivity shows how easily heat travels through the material. Moderate thermal conductivity ensures that the heat releases are align with the building's cooling cycle.
- Building Orientation and Openings: Assess the building's orientation in relation to prevailing winds and local climate to optimize the placement and size of openings for improved natural ventilation.

Active Cooling

- Air Changes per Hour (ACH): Calculate the number of times the air within a space is completely replaced in an hour. This measurement indicates the effectiveness of the ventilation system in circulating air and removing stale air.
- Cooling Fan Efficiency (CFE): Determine the ratio of the cooling effect achieved to the power consumed by the fans. This efficiency metric helps measure the effectiveness and energy usage of the fans.
- Efficiency: The efficiency of a device is determined by dividing the power it consumes by the power it delivers to perform its function.
- Fan-Use Rate: Determine the energy consumption per fan per day by multiplying the fan's power rate [W] by the number of hours of daily usage (or other time based range).
- Life Cycle Assessment: Calculate the CO^2 footprint of a device across its entire life cycle by assessing the kg of CO^2 emitted during stages of Material Extraction, Transport, Manufacturing and Assembly, Use, and End of Life.

- Airflow Rate:

$$Q = A * v \quad [m^3 / h]$$

A = Space Area [m2]
v = Air Velocity [m / s]

- Air Changes per Hour:

$$ACH = 3.6Q / V \quad [/ h]$$
$$ACH = G / (V * (v_i - v_e) \quad [/ h]$$

Q = Volumetric flow rate of air in cubic feet per minute [L/s]
V = Space Volume [m^3]
G = rate of moisture added to the room [g/h]
v_i = absolute humidity of the internal (indoor) air [g/m^3]
$v_{e\,=}$ absolute humidity of the external (outdoor) air [g/m^3]

- Cooling Fan Efficiency (CFE):

$$CFE = CE / FPC \quad [\%]$$

CE = Cooling Effect [°C]
FPC = Fan Power Consumption [W]

- Efficiency / COP:

$$Л = P_{out} / P_{in} \quad [\%]$$

$P_{out\,=}$ = Power output [W]
P_{in} = Power input [W]

- Fan-Use Rate:

$$FUR = FPC / FU \quad [\%]$$

FPC = Fan Power Consumption [W]
FU = Fan Use [h / day]

- Life Cycle Assessment:

$$LCA = [kg\ CO_2]$$

Material Extraction
Transport
Manufacturing and Assembly
Use
End of Life

Appendix 3.2: Formulas for determine effectiveness per cooling strategy

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